Image credit: DESY

Stellar tidal disruption events

multi-messenger transients

TDAMM (Aug 23, 2022)

Sjoert van Velzen, Leiden Observatory

Key collaborators: Suvi Gezari, ZTFbh team, James Miller-Jones, Nicholas Stone, Robert Stein, Marek Kowalski, DJ Pasham

Fundamental Questions

Are black holes spinning?

Is accretion physics scale invariant?

Black hole genesis in the early universe

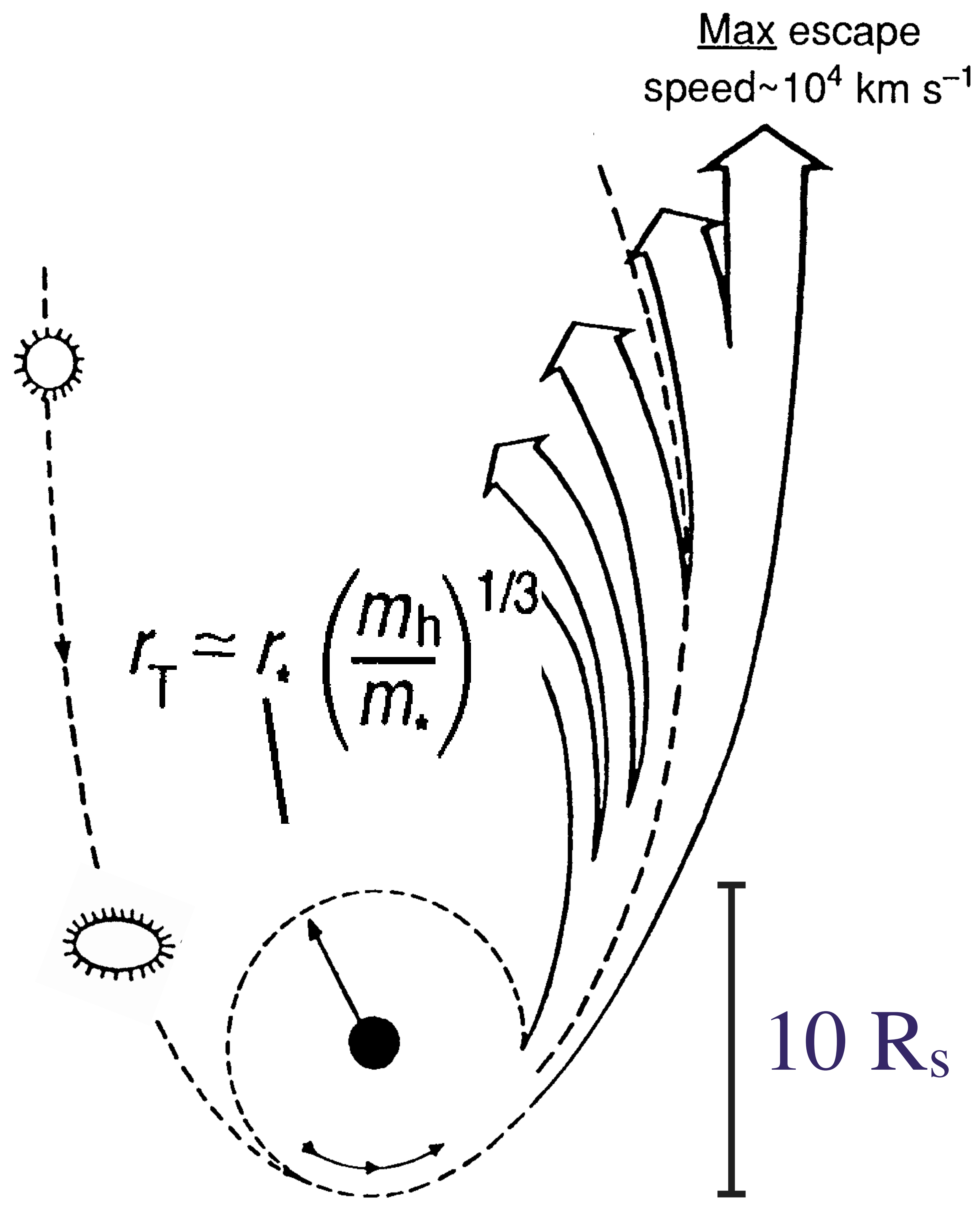
Image credit: Wikimedia

A new tool to study black holes in *quiescent* galaxies

Artis impression Image credit: NASA, van Velzen et al.
Simulation image: Guillochon et al.

Stellar tidal disruption events (TDEs)

- Star passes within Roche radius (r_T)
- Half of the debris remains bound
- Steep fallback rate: $t^{-5/3}$
- Rare events: ~10^4 yr wait time per galaxy
- $M > 10^8\ M_\odot$, Roche radius inside black hole horizon



Rees (1988)

Fundamental Questions

Are black holes spinning?

TDE rate at high black hole mass

Is accretion physics scale invariant?

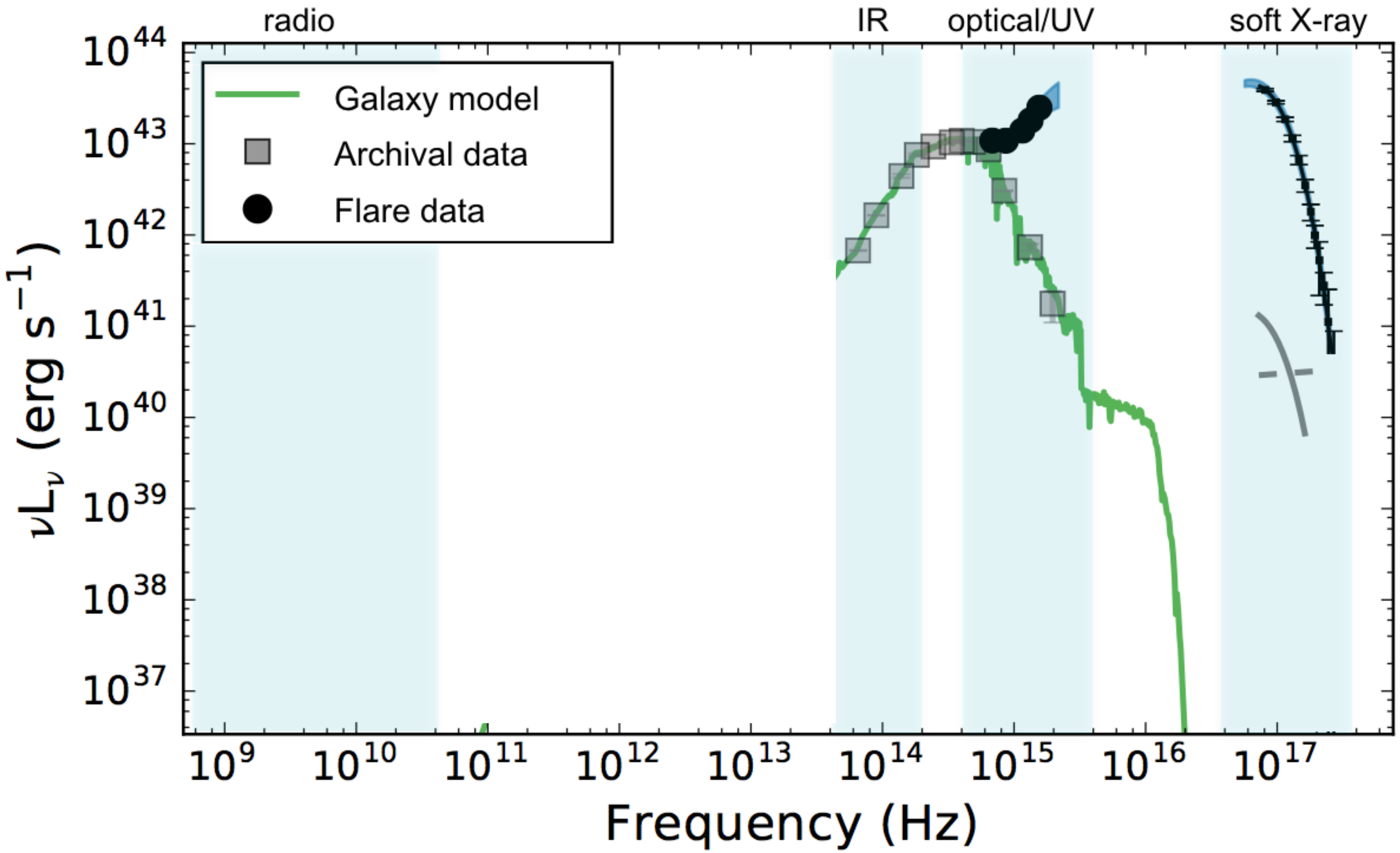
Radio + X-ray monitoring of TDEs

Black hole genesis in early universe

TDE rate in low-mass galaxies

Image credit: Wikimedia

Spectrum of a tidal disruption flare



van Velzen et al. (Science, 2016);
ASASSN-14li (Holoien et al. 2016)

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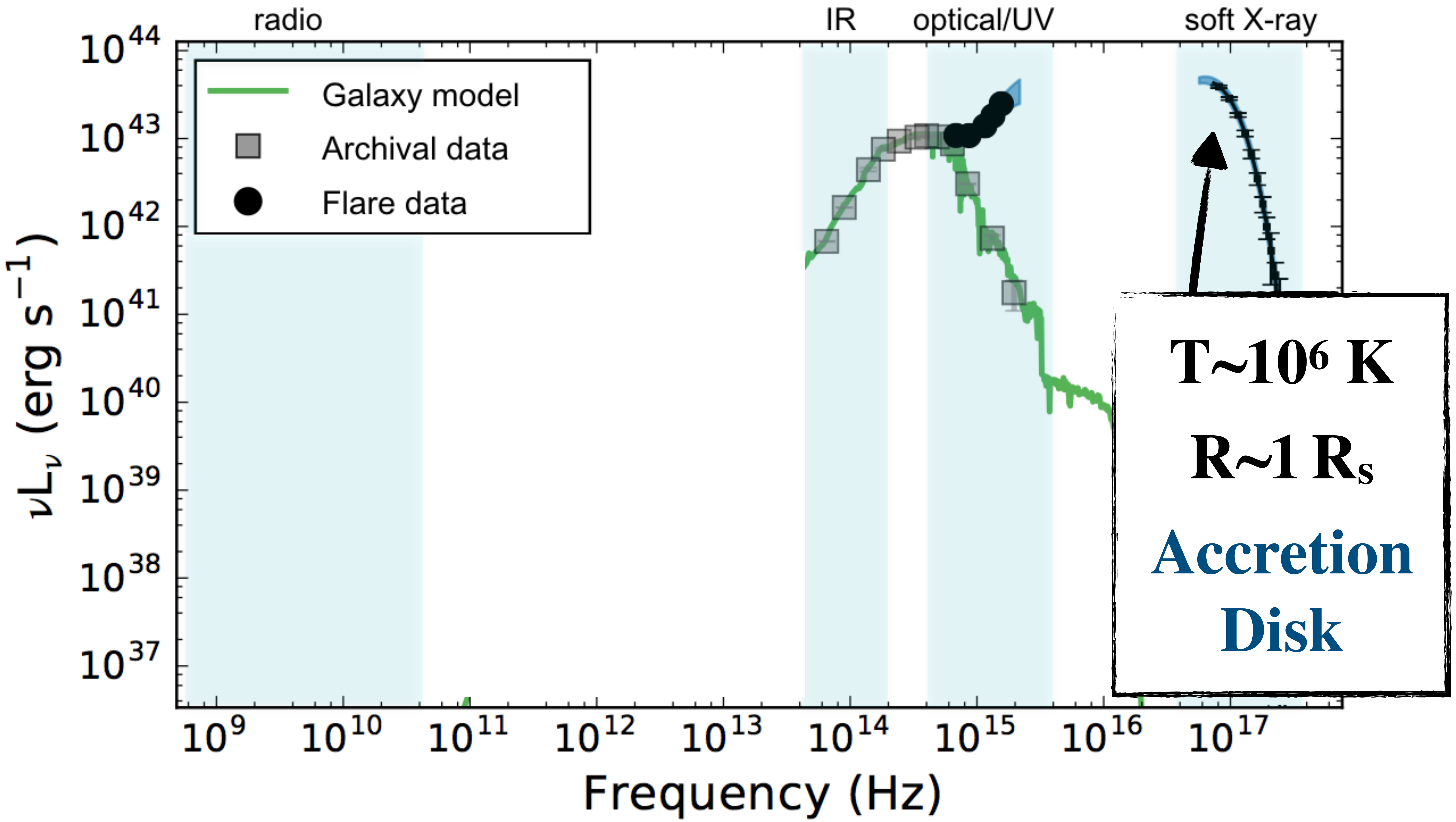

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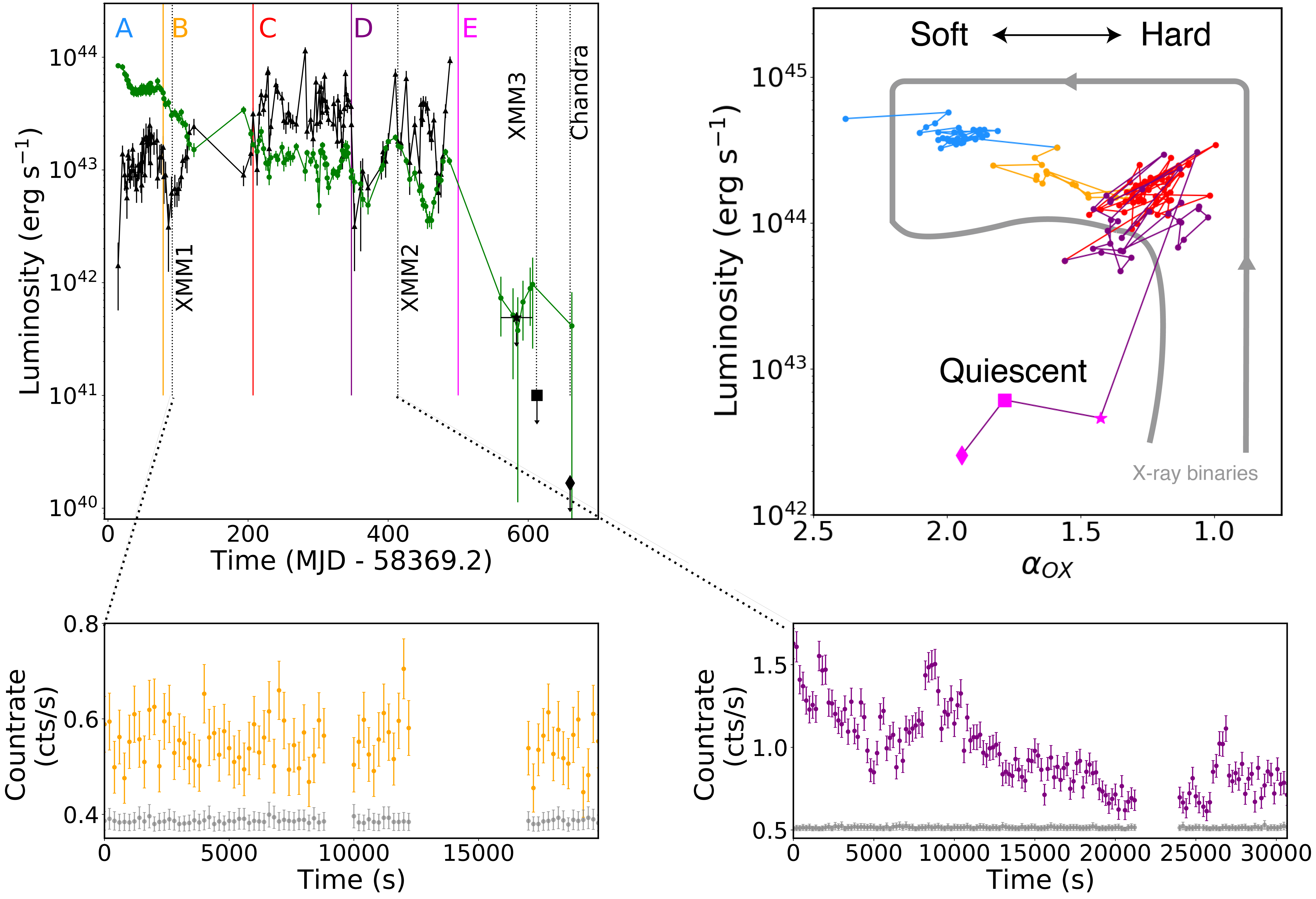
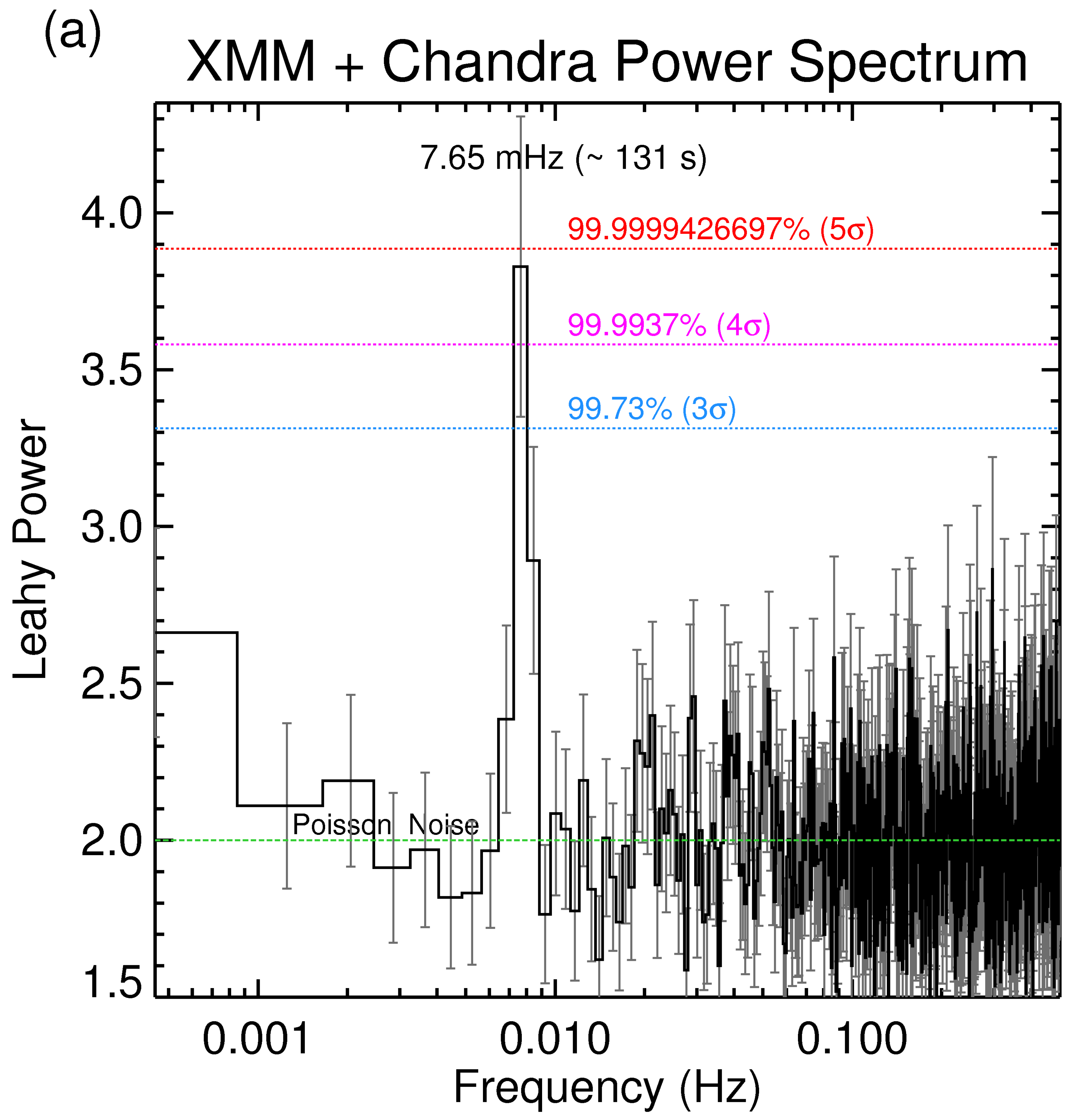
X-ray state changes

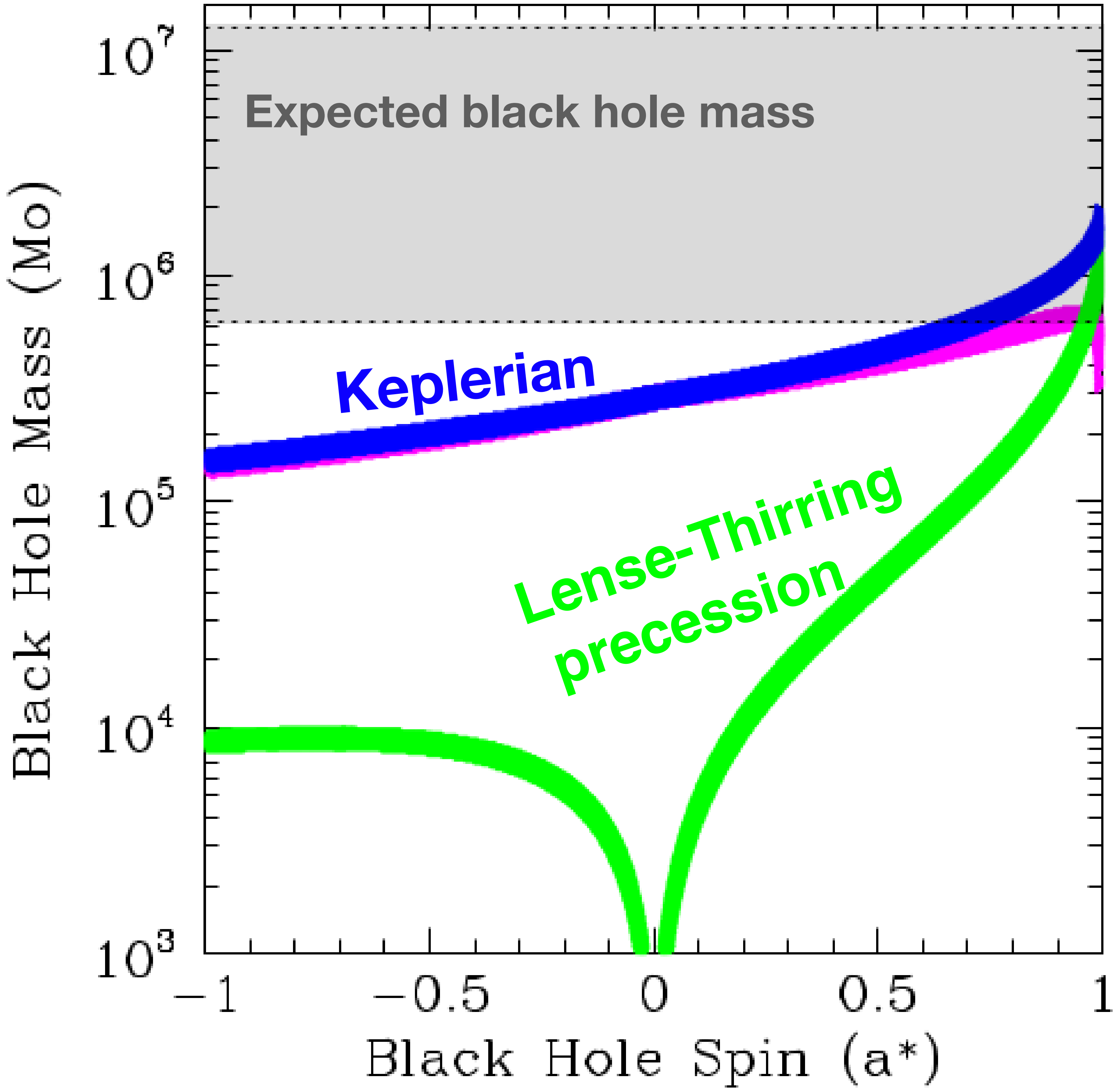


AT 2018fyk

Wevers et al. (2021)

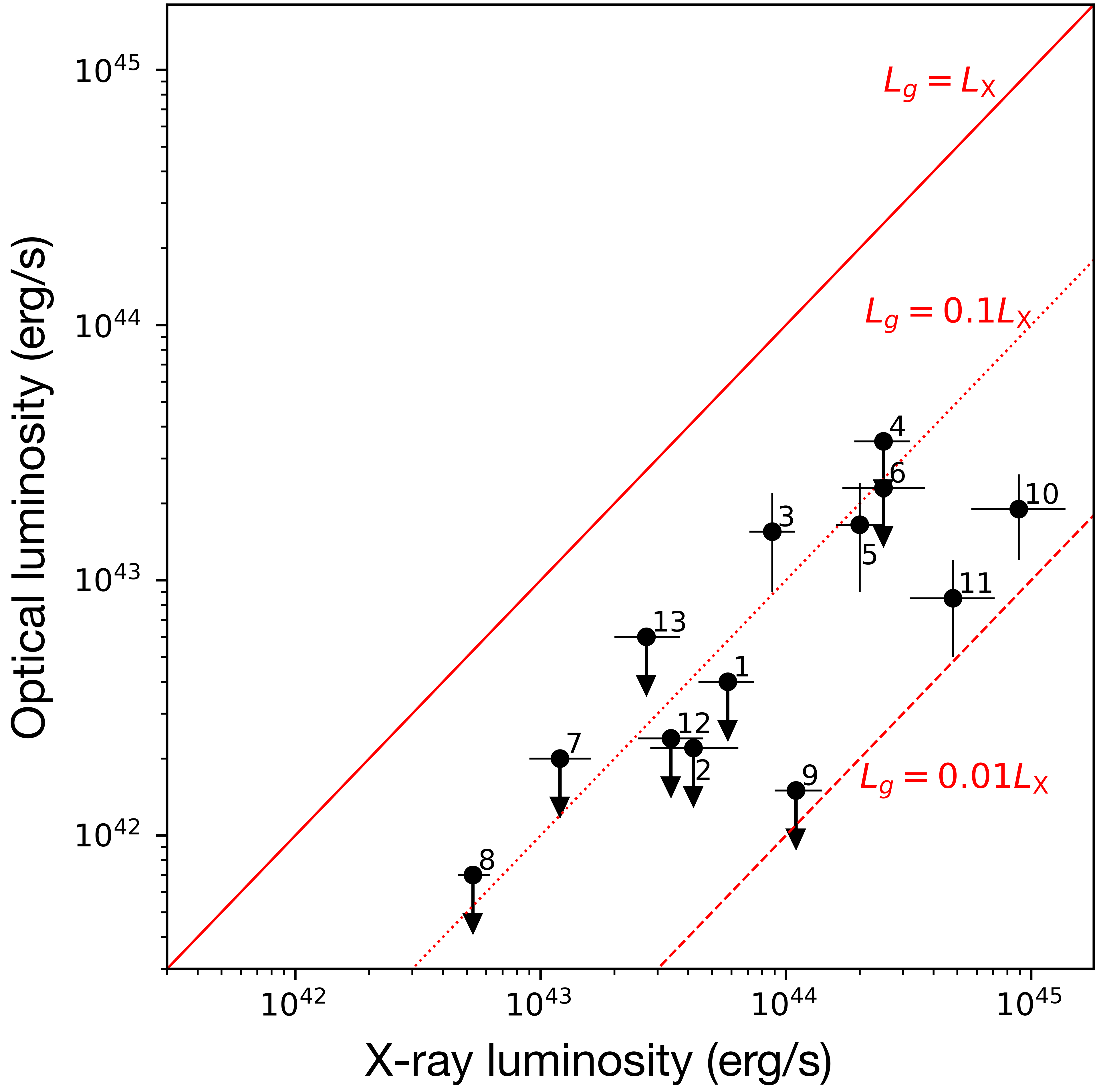
QPO detection: probe spin





Pasham et al. (2019)
observations of ASASSN-14li

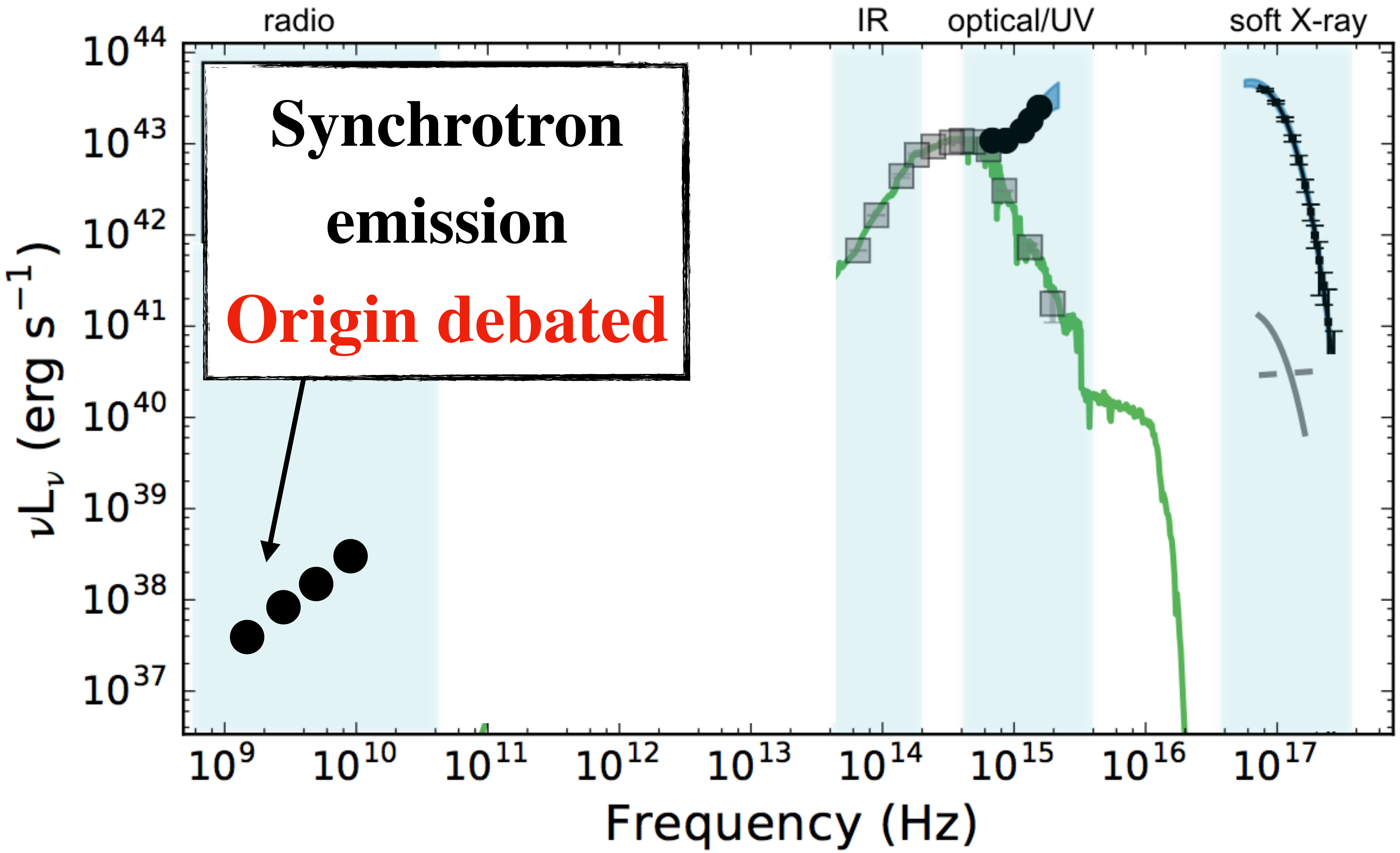
Results from SRG/eROSITA



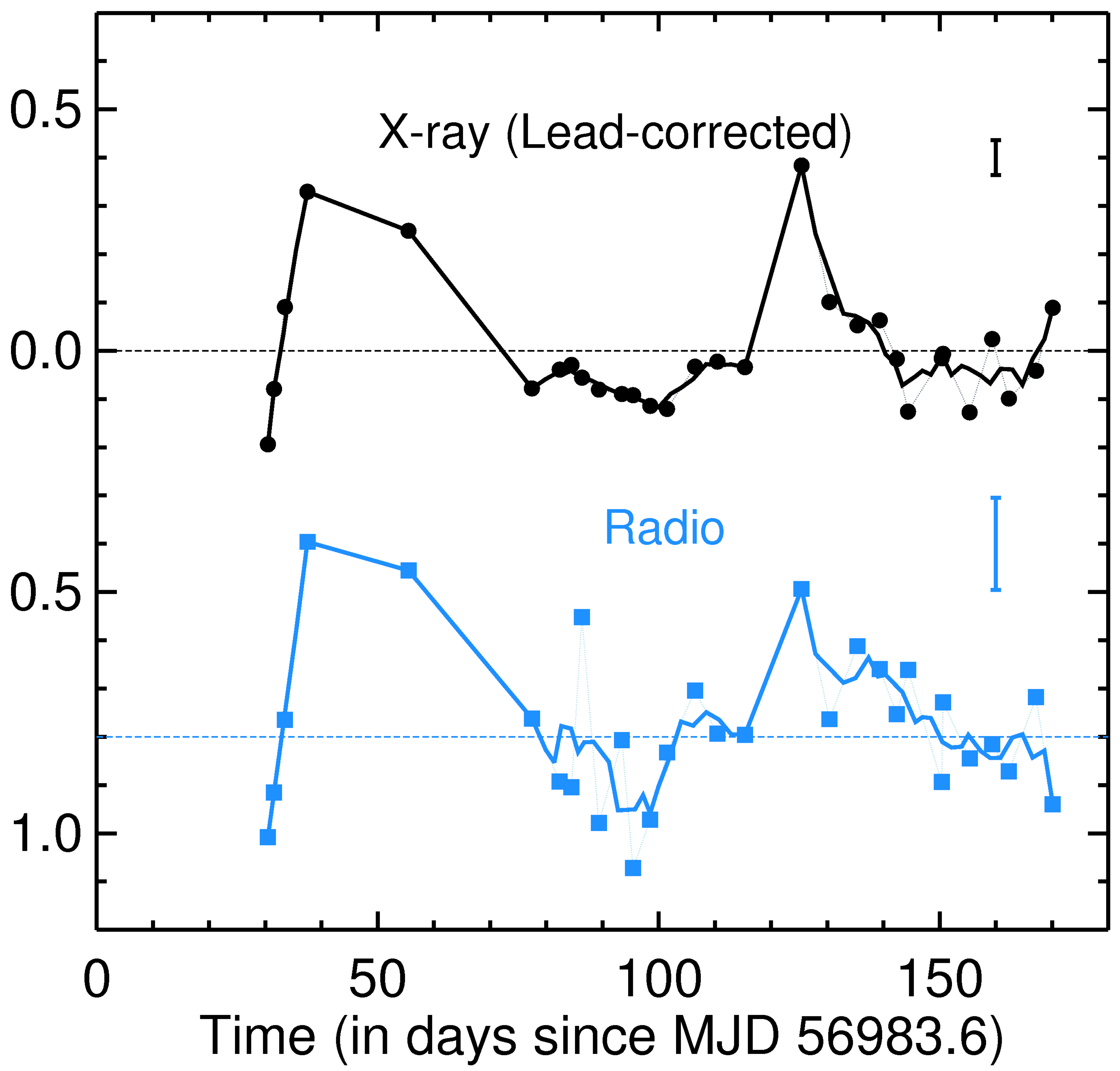
- 13 X-ray selected TDEs
  - Soft spectra, large flux increase
- Optical dim
- Relatively high mass host galaxies
- X-ray rate lower than optical rate

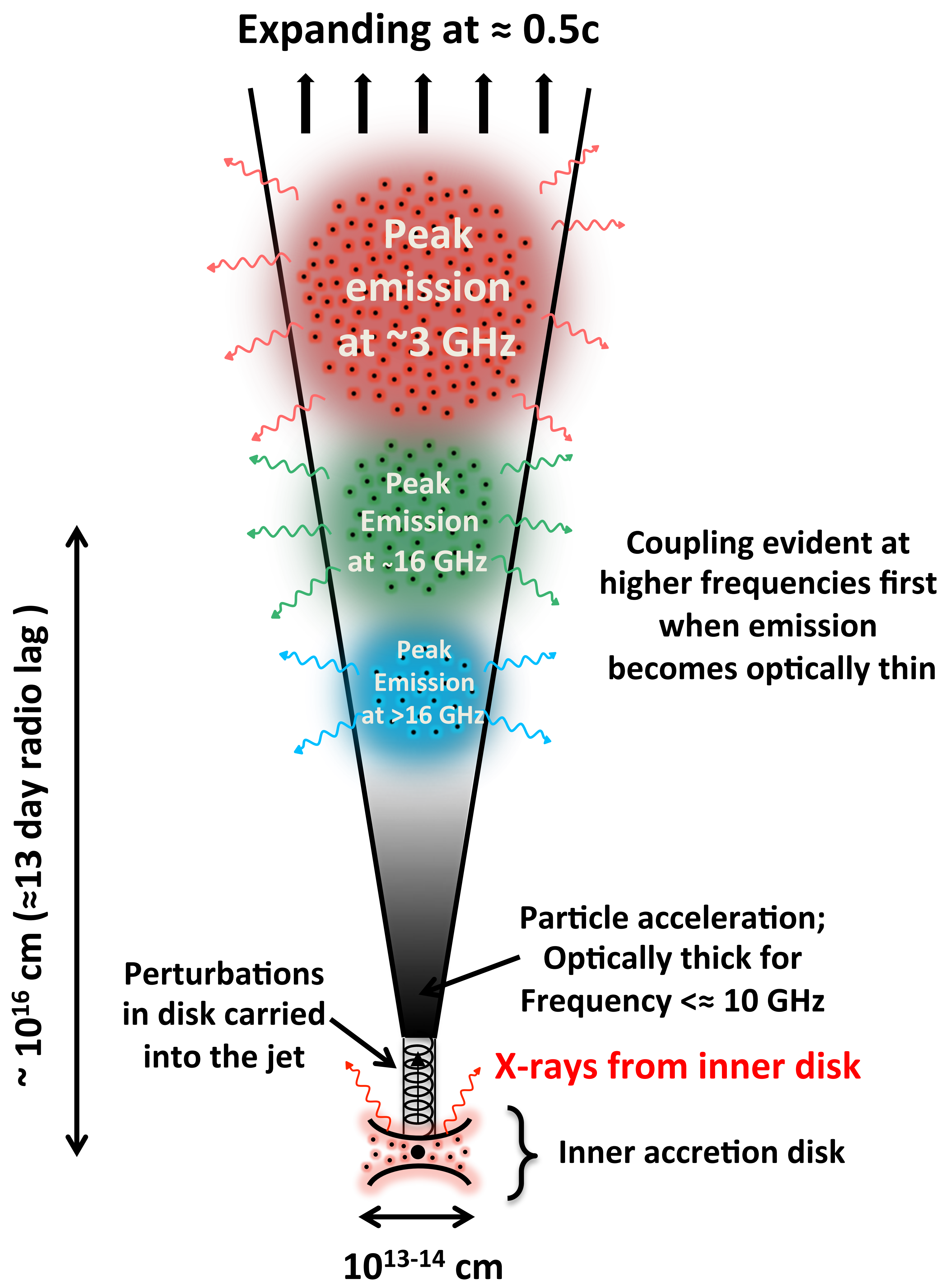
Sazonov et al. (arXiv:2108.02449)

Spectrum of a tidal disruption flare



Radio / X-ray cross-correlation

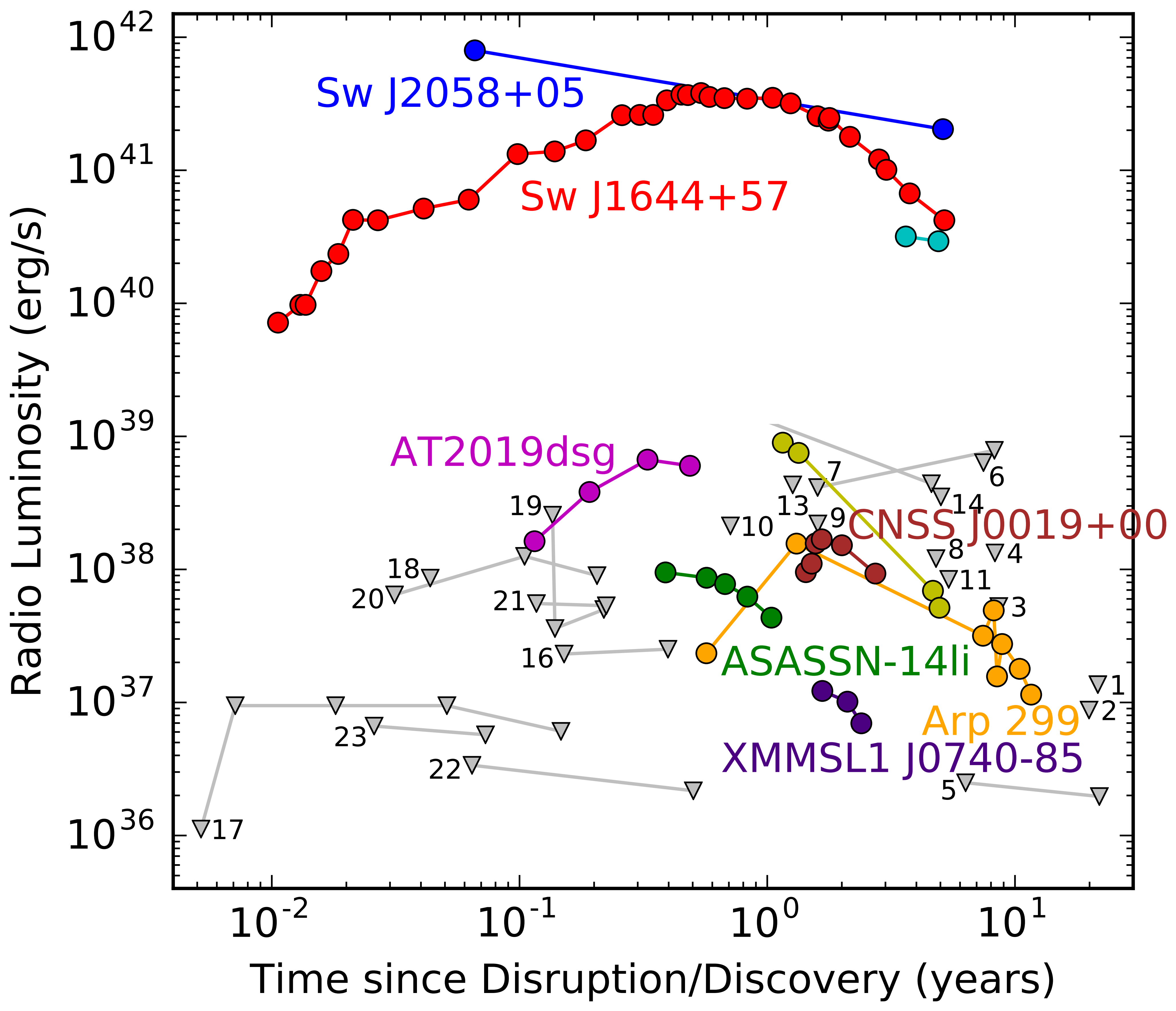




Pasham & van Velzen (2017), based on ASASSN-14li

~10 TDEs detected via radio follow-up

- High luminosity jetted TDEs: powered by BH (Sw J1644+57)
- Origin of low-luminosity radio emission from thermal TDEs debated:
  - (sub)-relativistic jet
  - outflow from disk
  - unbound stellar debris
- ~1/4 of thermal TDEs detected in radio
- Few radio-selected TDEs candidates (Mooley eta al. 2016; Anderson et al. 2019; Somalwar et al. 2021)

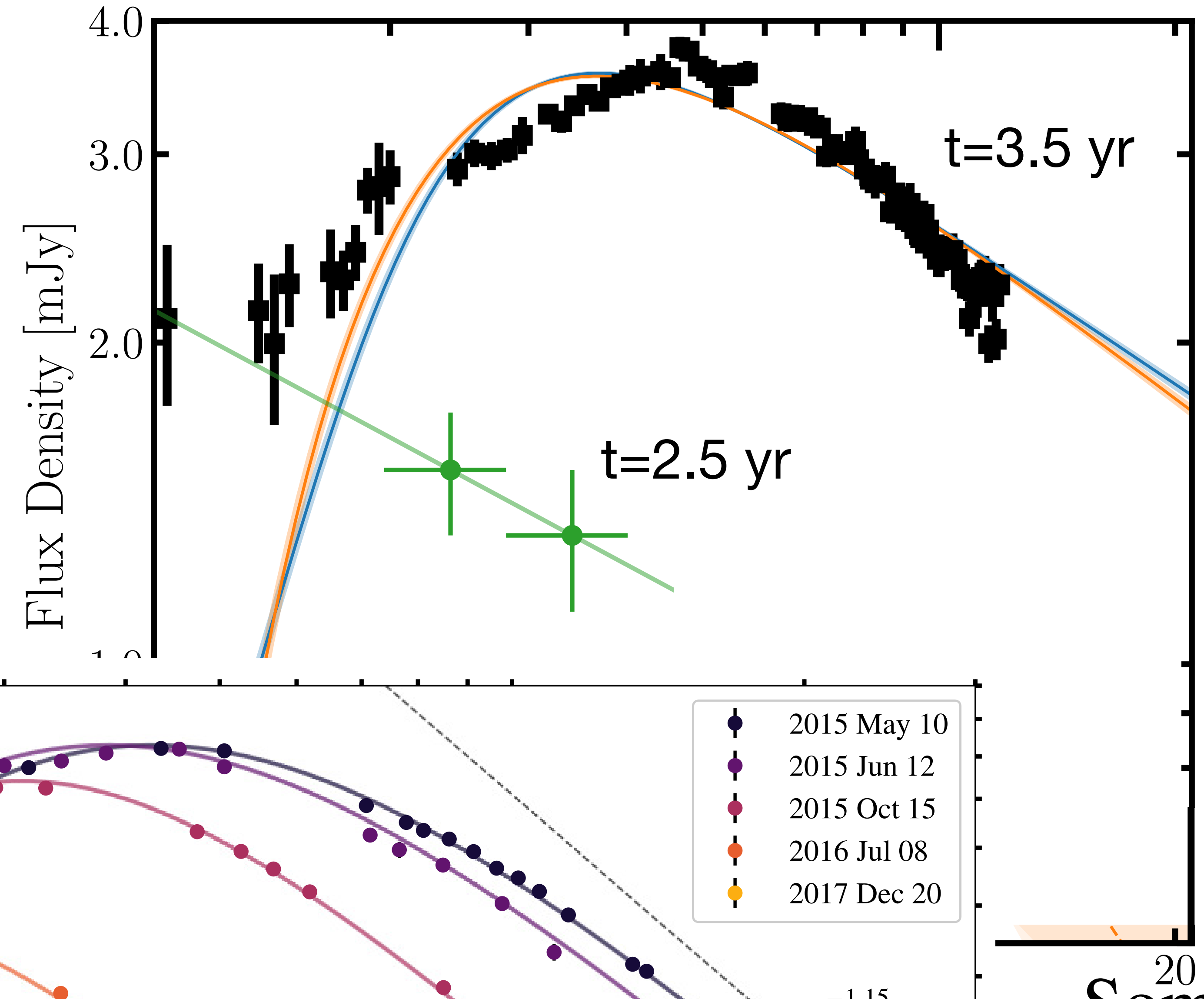


Alexander, van Velzen, et al. (2020)

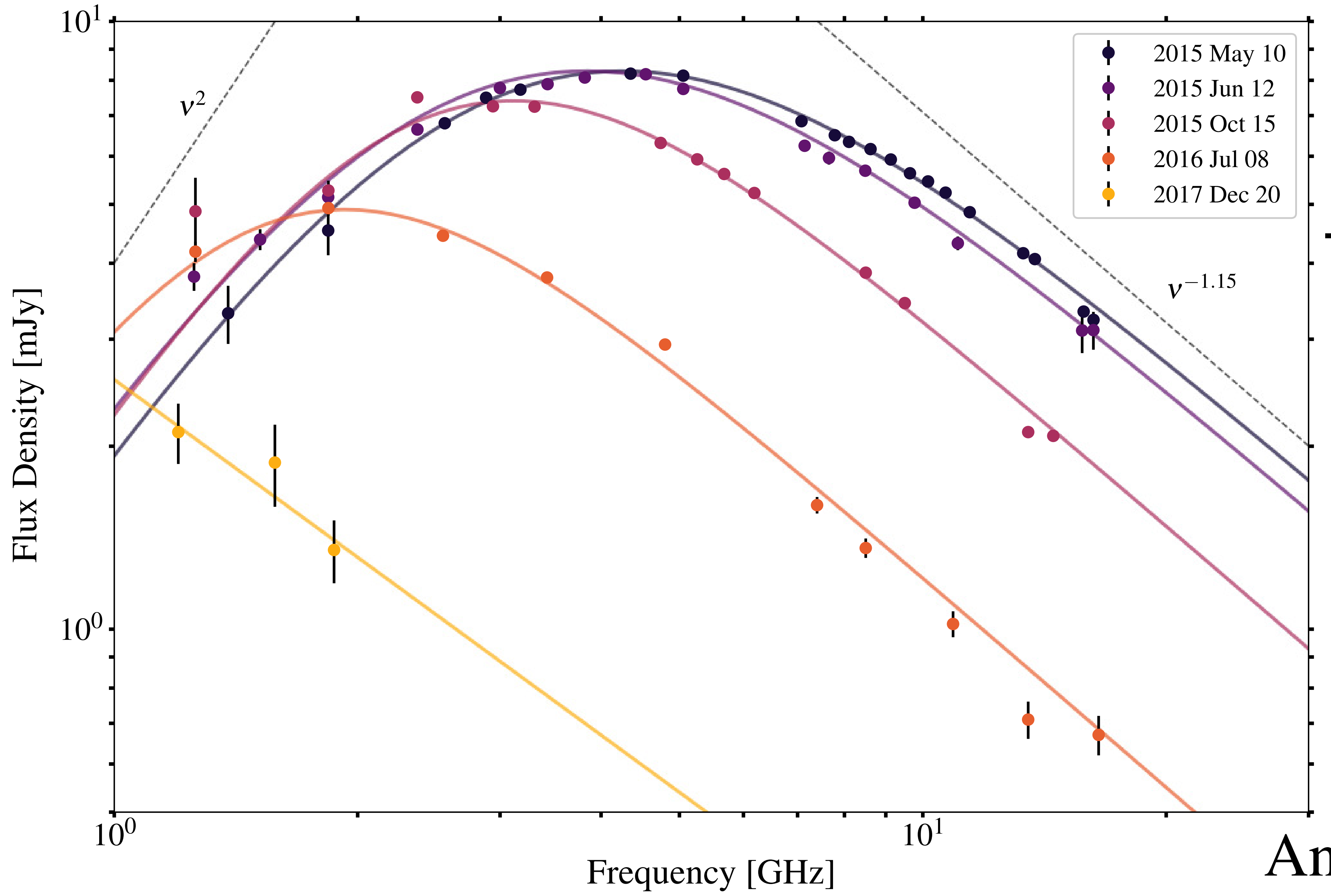
Radio transients on ~1 year timescale

Are these due to stellar tidal disruptions?

- Possible, but both sources show evidence for accretion prior to the radio flare



Somalwar+21



Anderson+19

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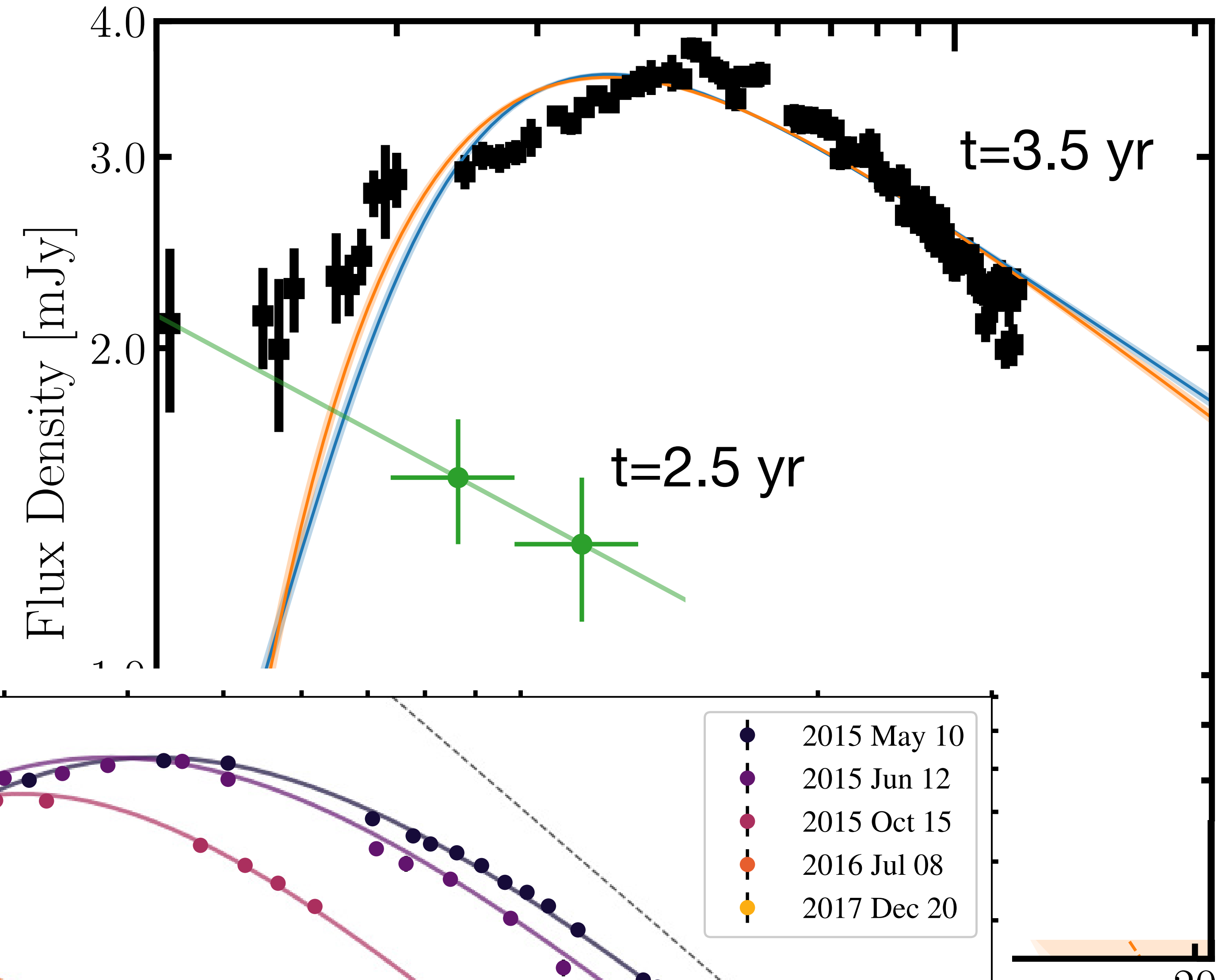
- IR flare in one case (VT J1548)
    - AGN with large IR flares are also more radio-loud (Dai+20)



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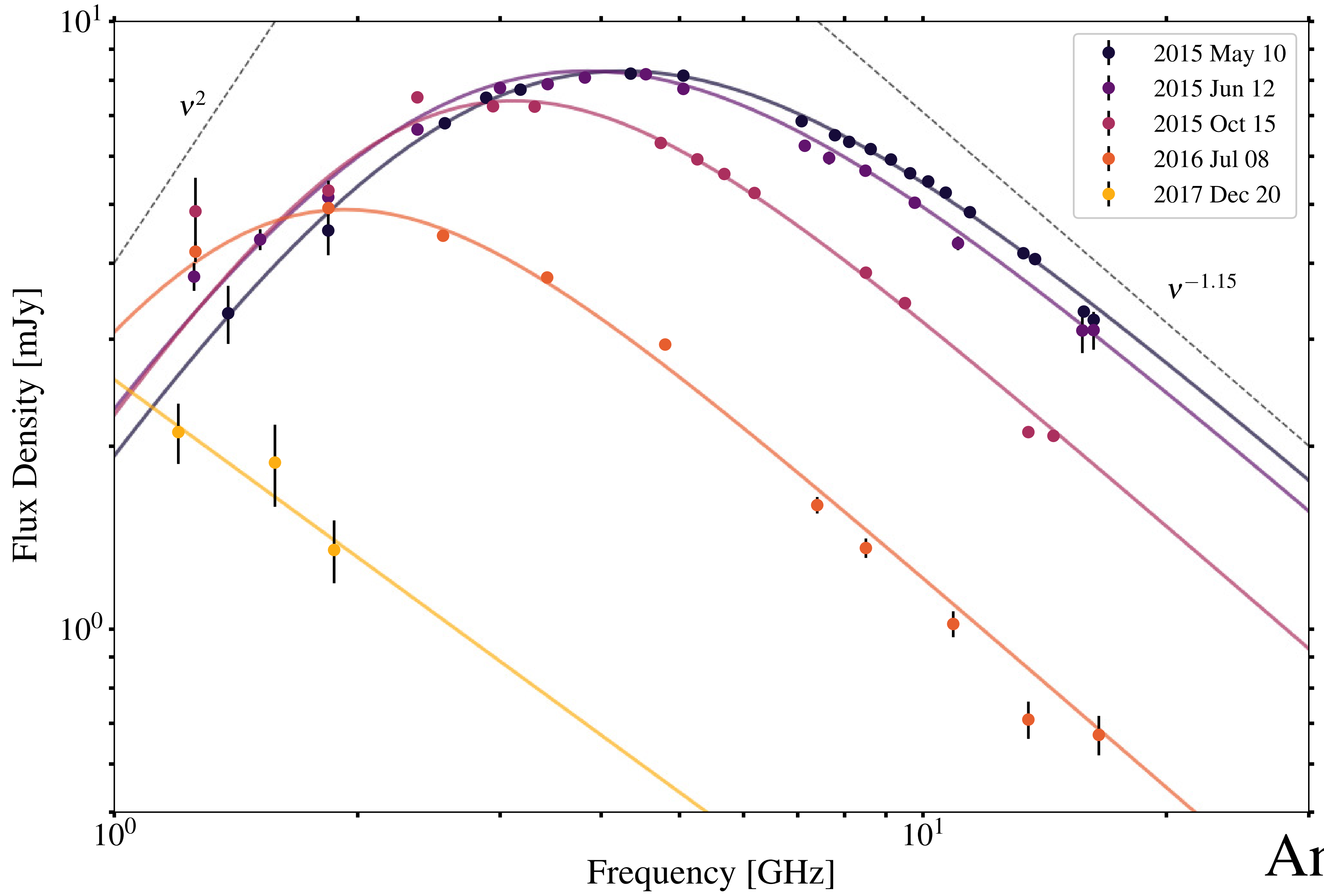

Anderson+19

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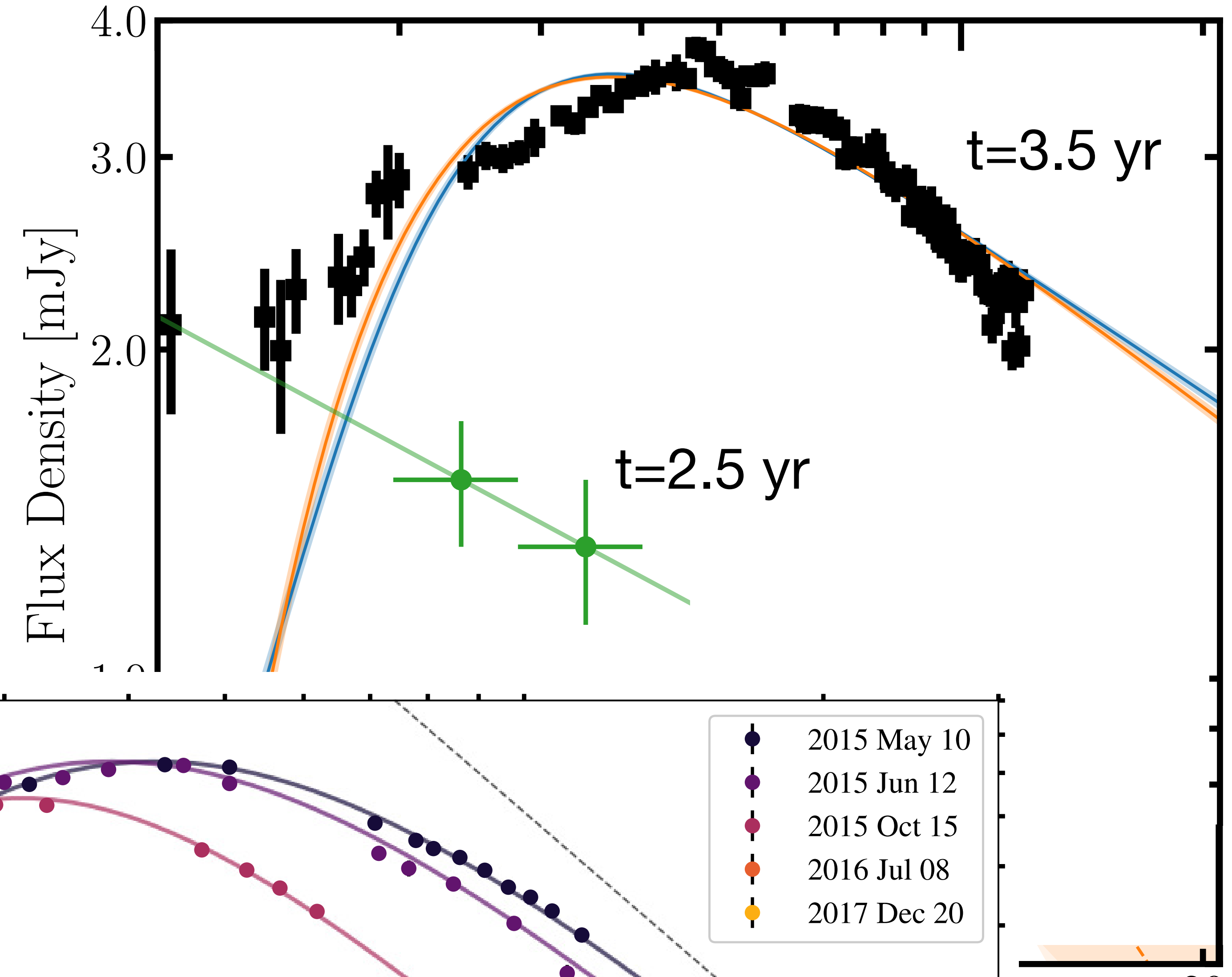
- Connection to state transition of the accretion disk?



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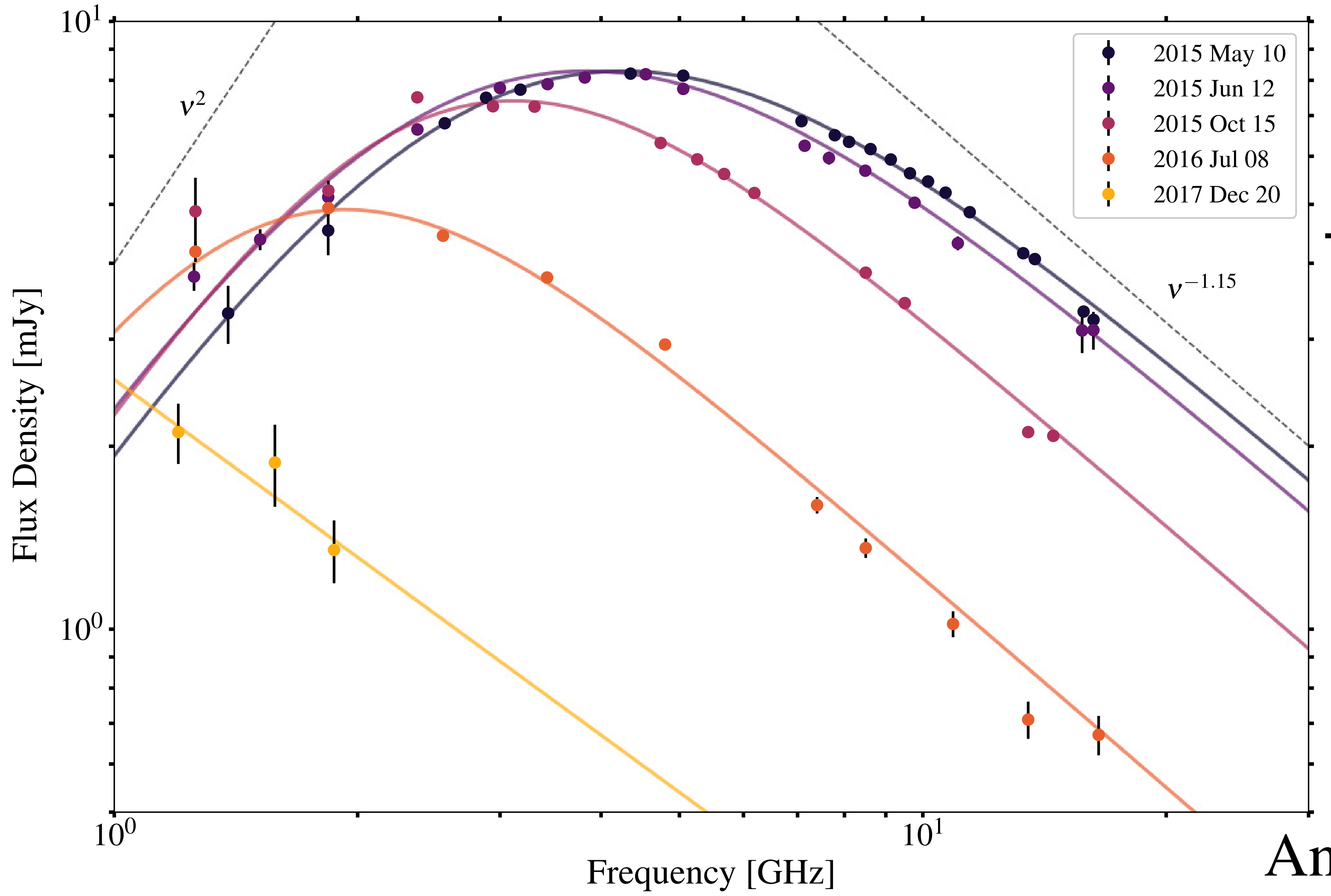
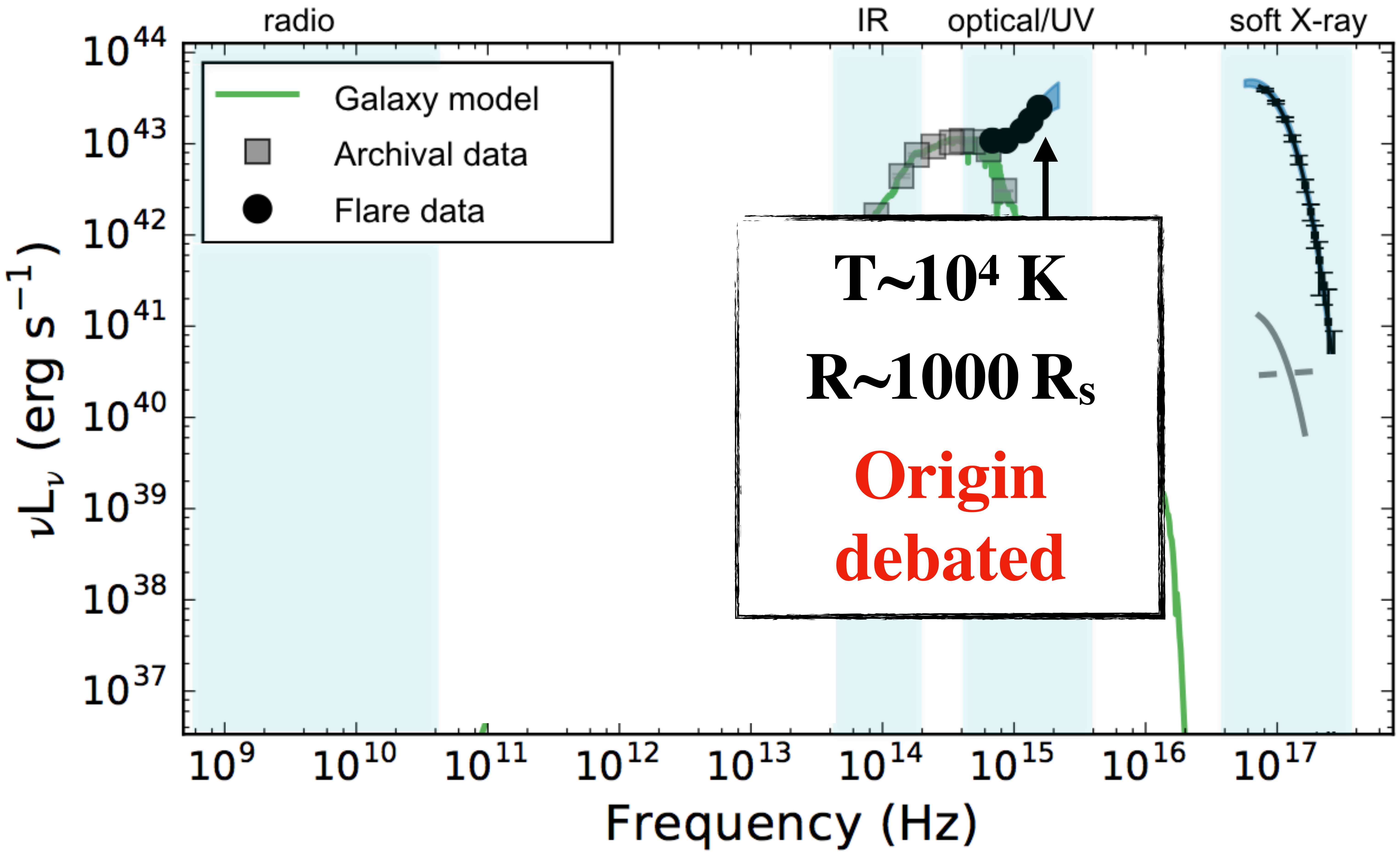


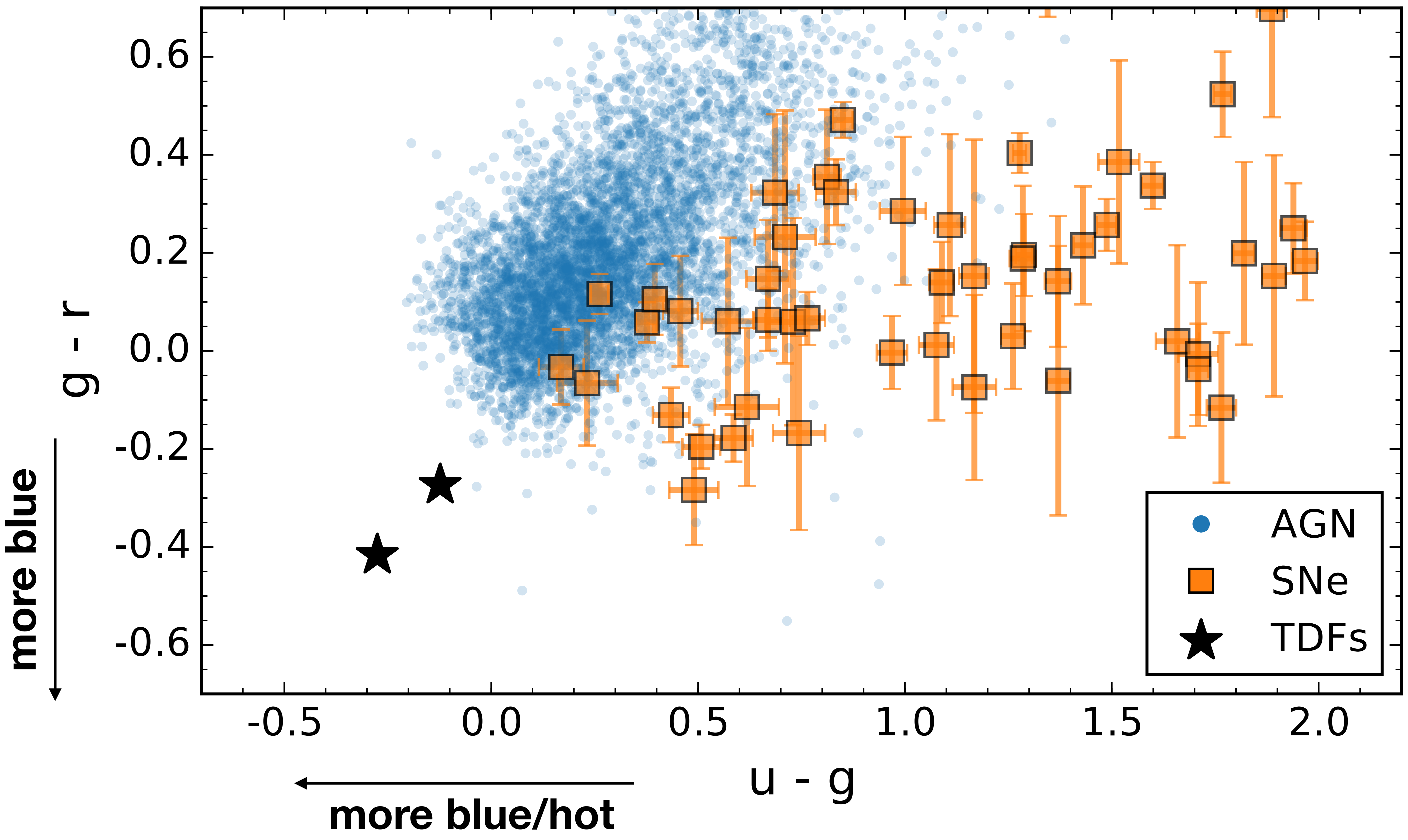
Anderson+19

Spectrum of a tidal disruption flare



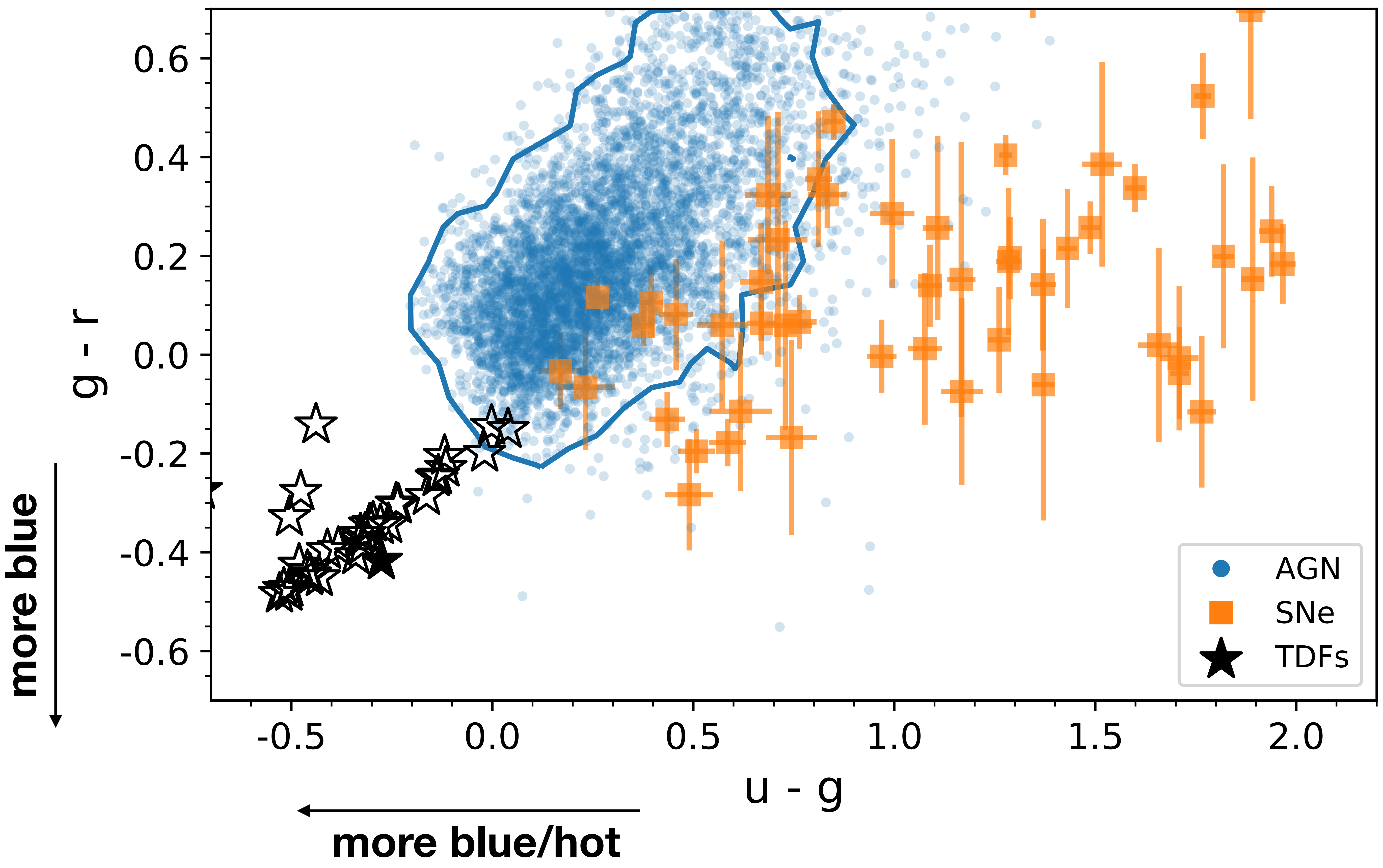
van Velzen et al. (Science, 2016);
ASASSN-14li (Holoien et al. 2016)

TDE locus in optical surveys (2011)



adapted from van Velzen et al. (2011)

TDE locus in optical surveys (2022)



Now including 30 TDEs from ZTF-I
(van Velzen et al. 2021; Hammerstein et al. 2022)

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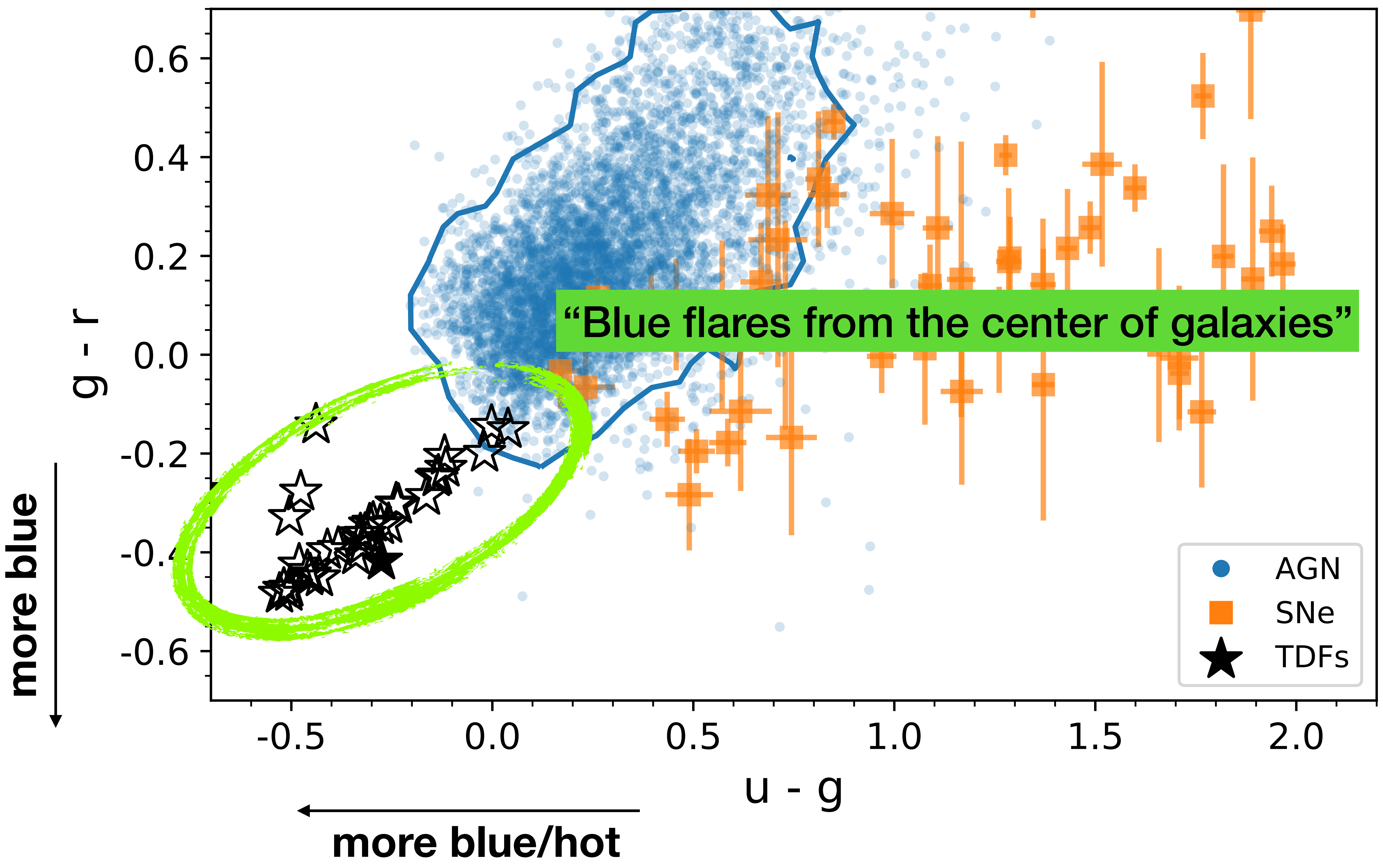

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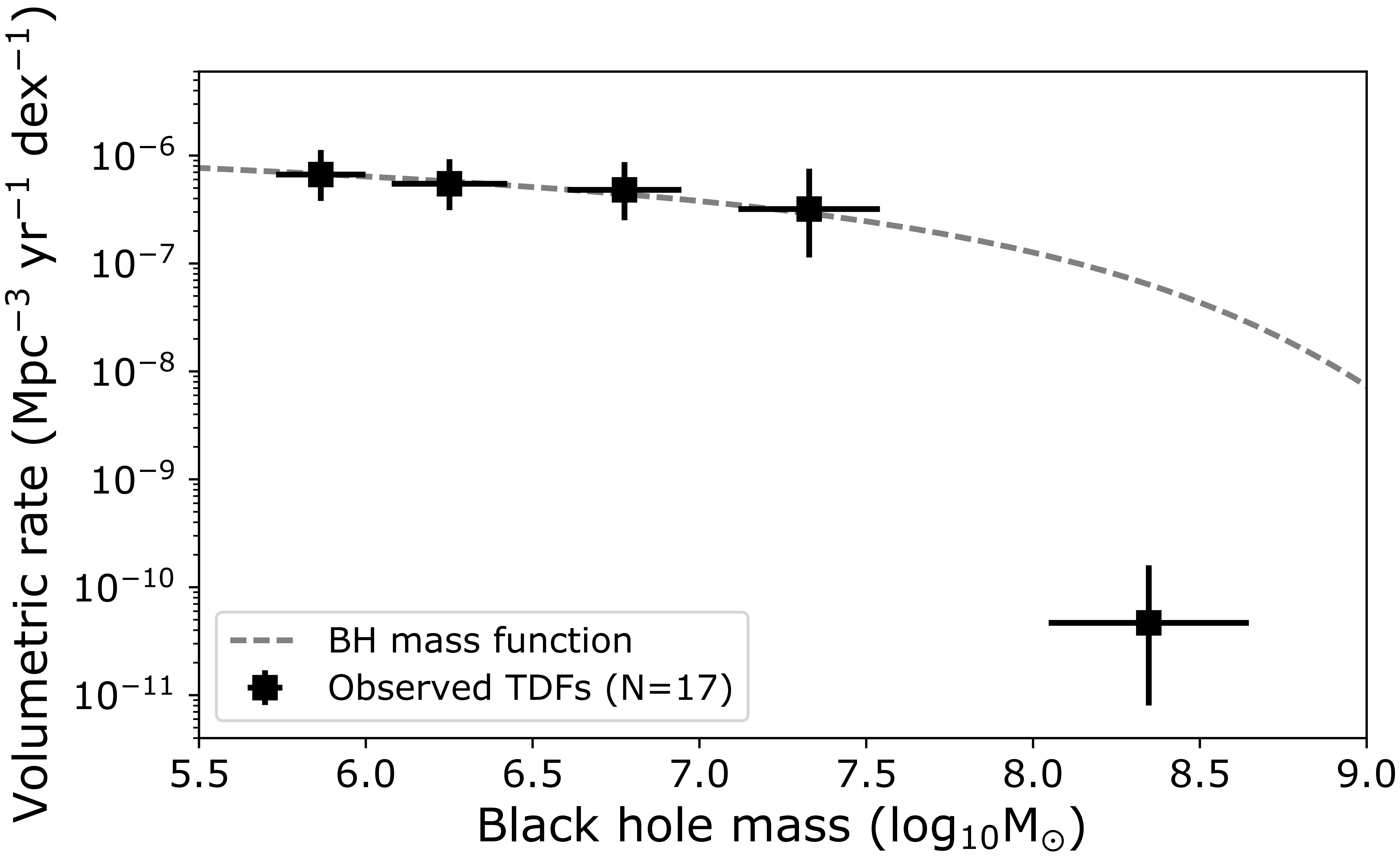
The event rate as a function of black hole mass



Based on van Velzen (2018); updated with data from
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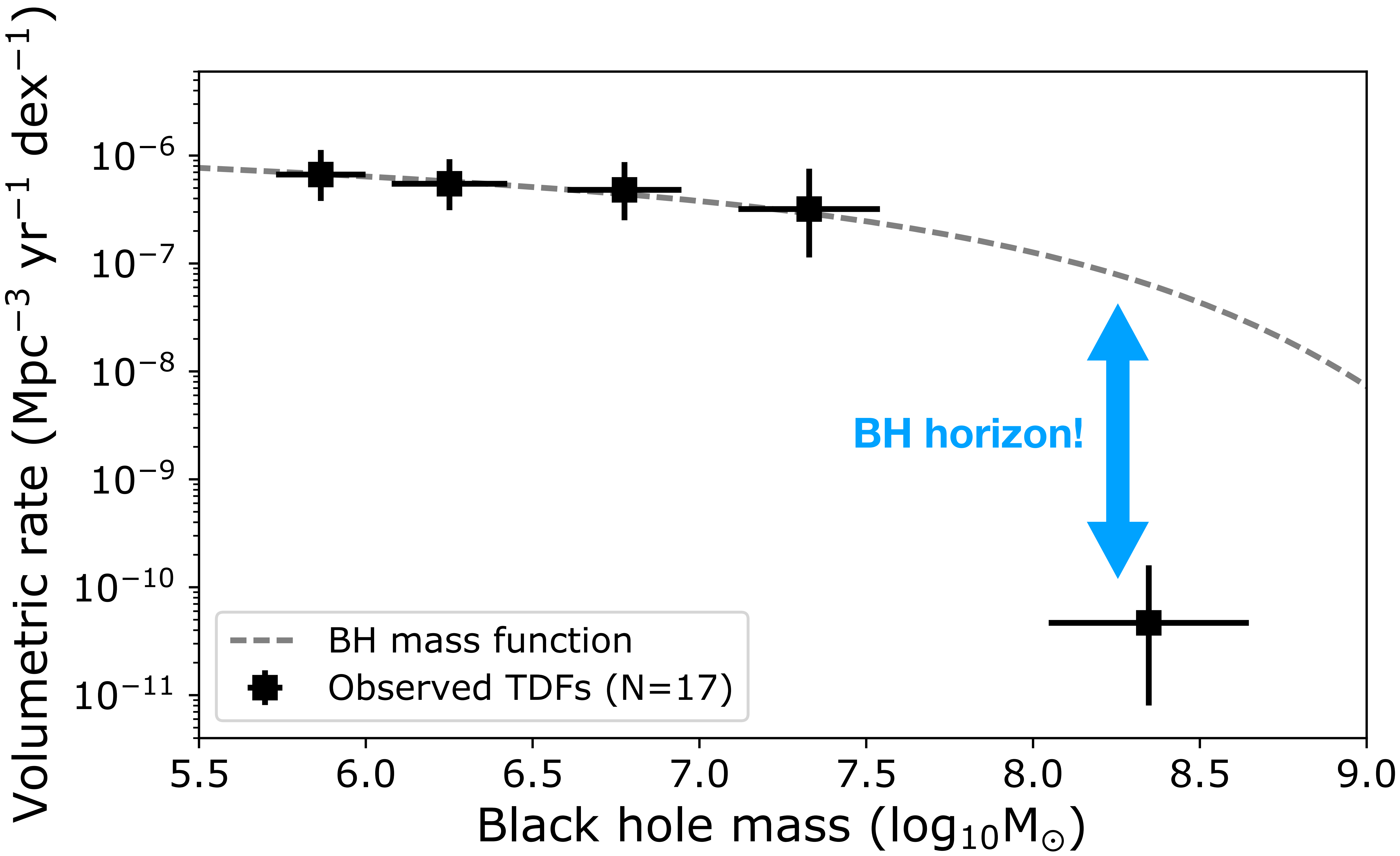

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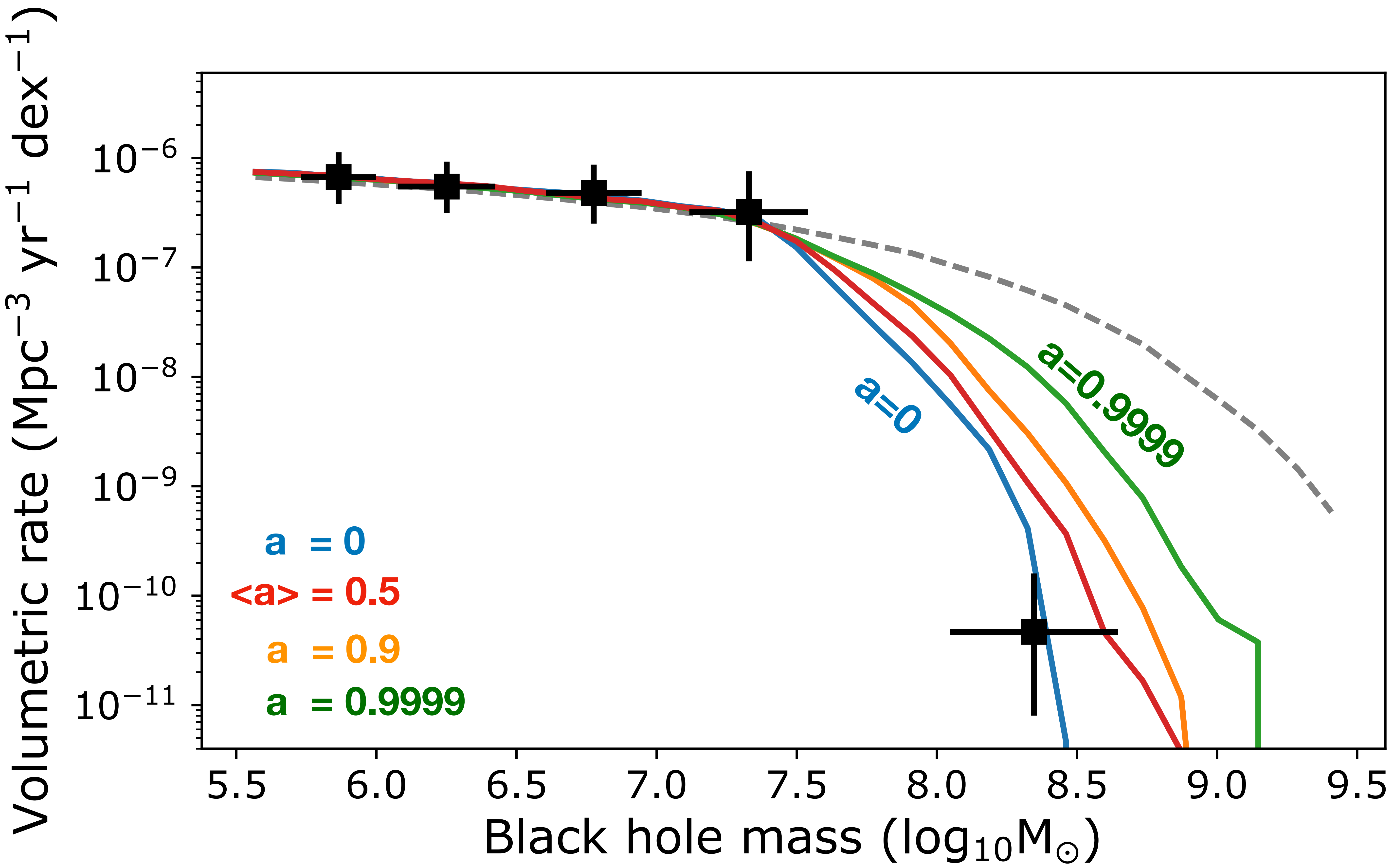
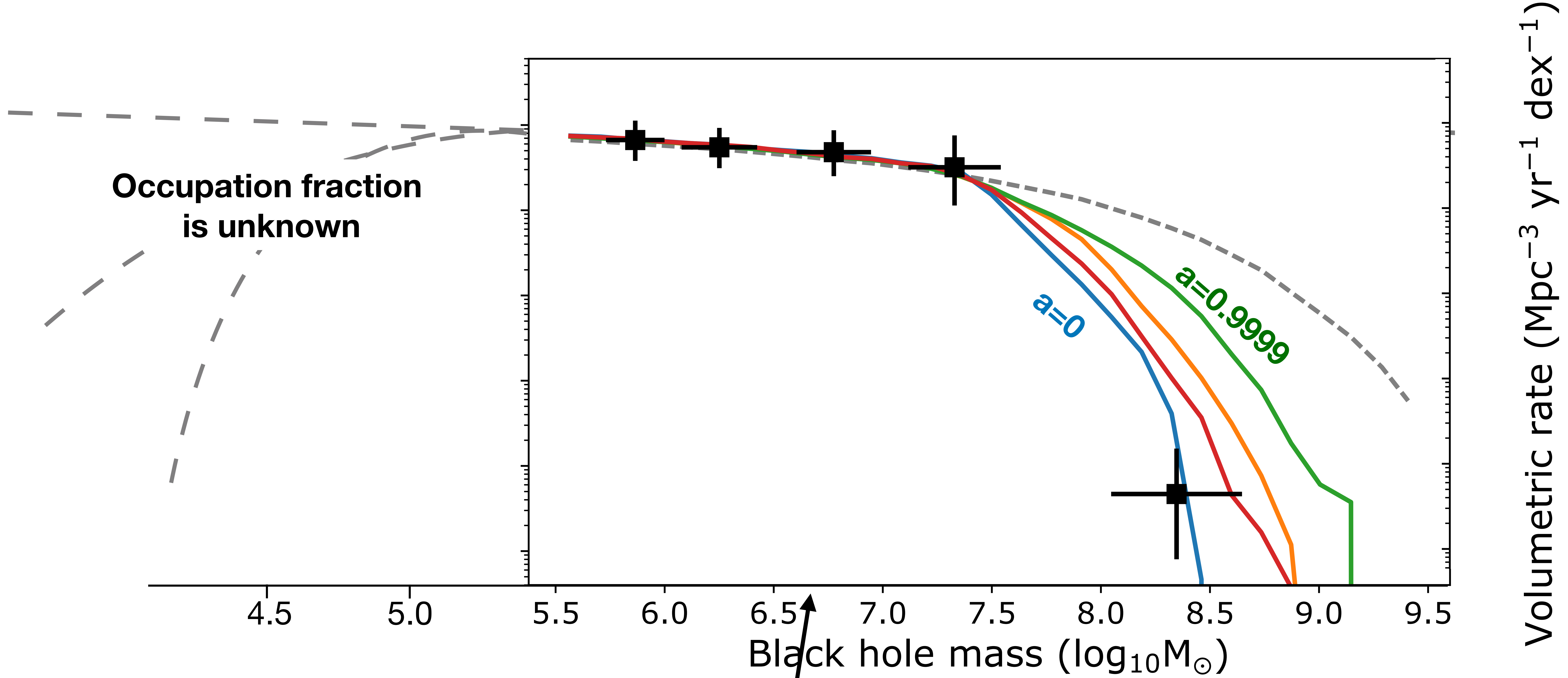
Measuring the average spin of quiescent black holes



ASASSN-15lh: Leloudas et al. (2016)

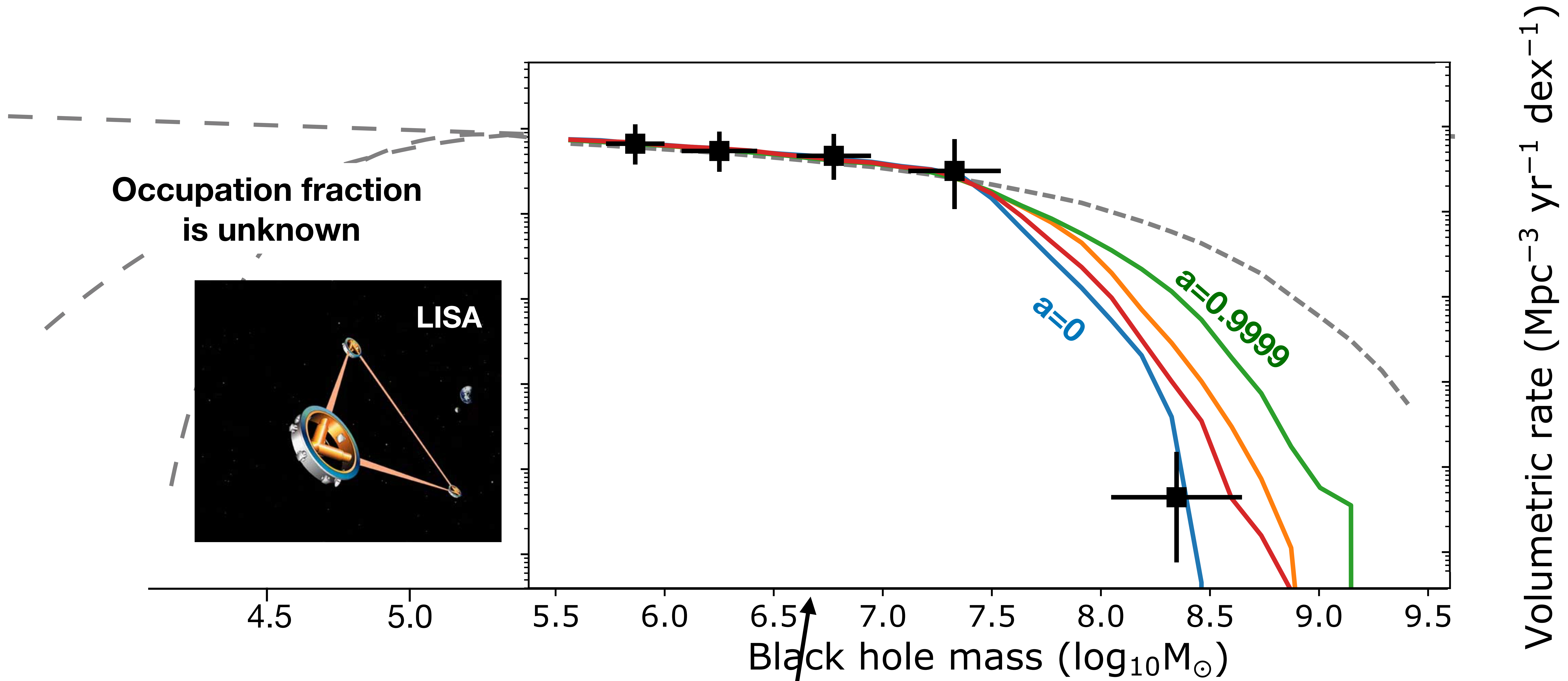
Figure: Stone & van Velzen (2022, in prep)


Occupation fraction
is unknown
a=0
a=0.9999
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
9.0
9.5
Black hole mass ($\log_{10} M_\odot$)
Volumetric rate ($\mathrm{Mpc}^{-3}\ \mathrm{yr}^{-1}\ \mathrm{dex}^{-1}$)


Dwarf galaxies


We are here (Sgr A*)


Elliptical galaxies


Occupation fraction
is unknown
LISA
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4.5
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Black hole mass ($\log_{10} M_\odot$)
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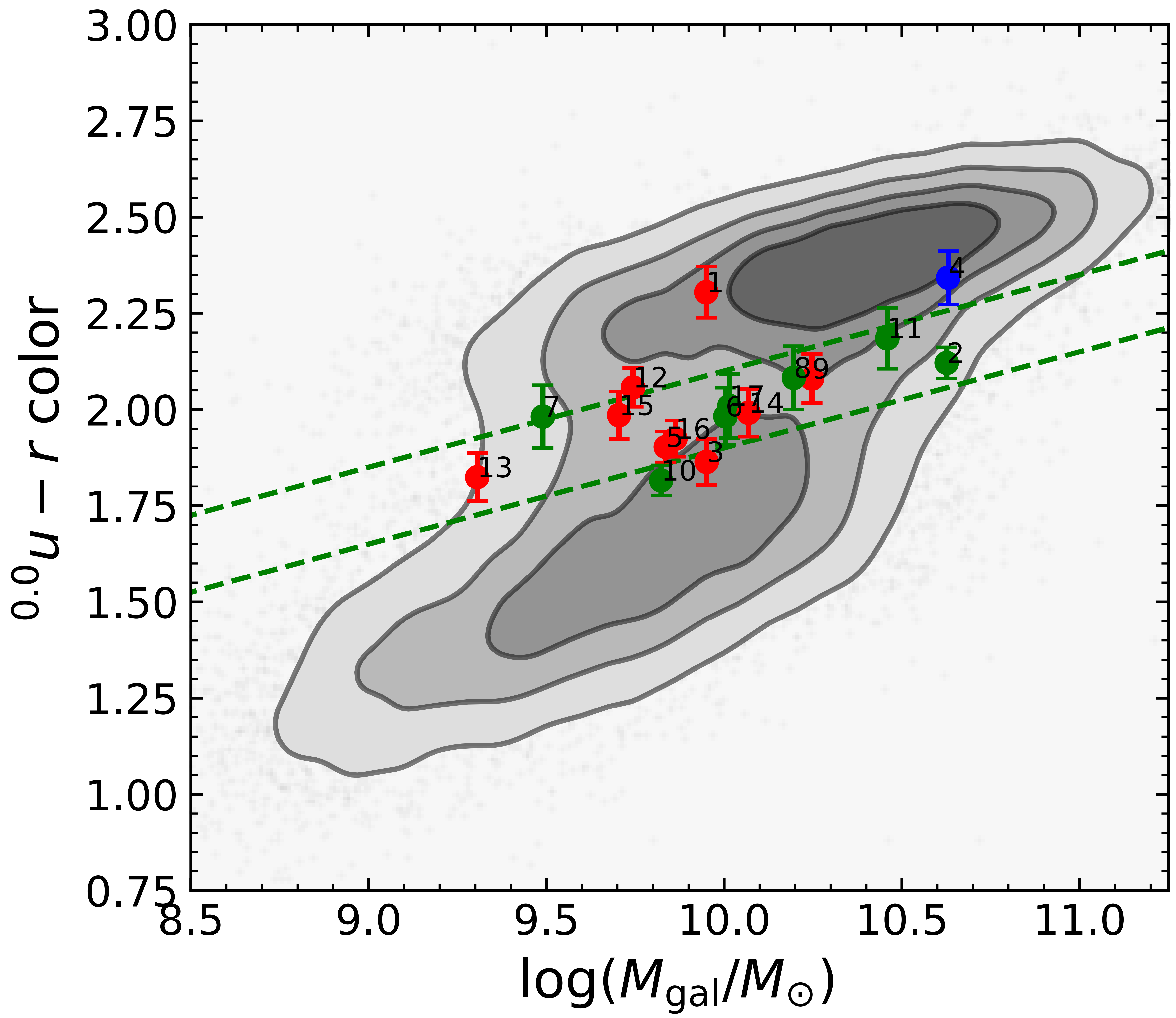
Host galaxies: preference for “green valley”



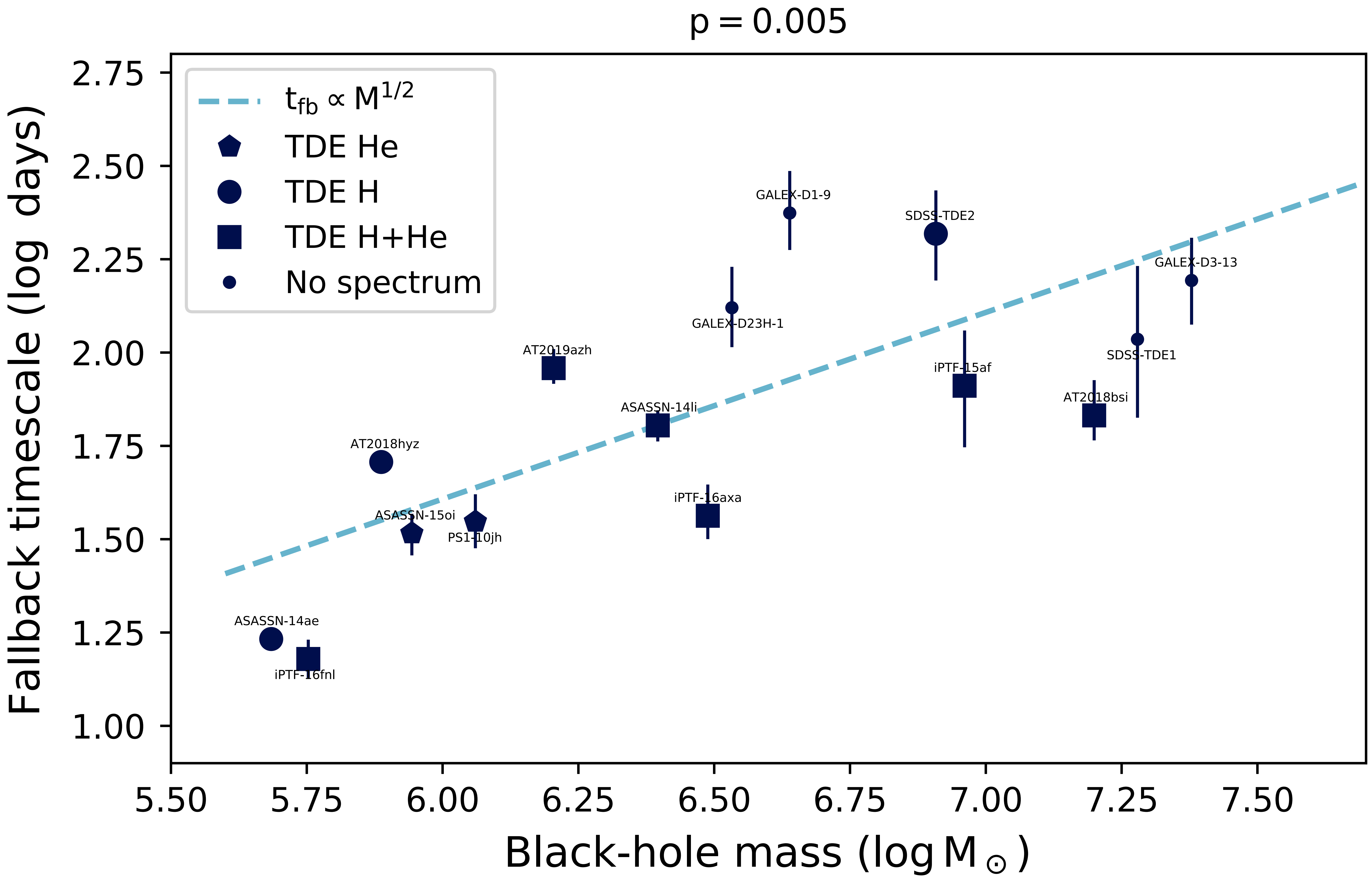
65% of TDEs in green valley compared to 10% of normal galaxies

Hammerstein et al. 2021

Similar to post-starburst preference

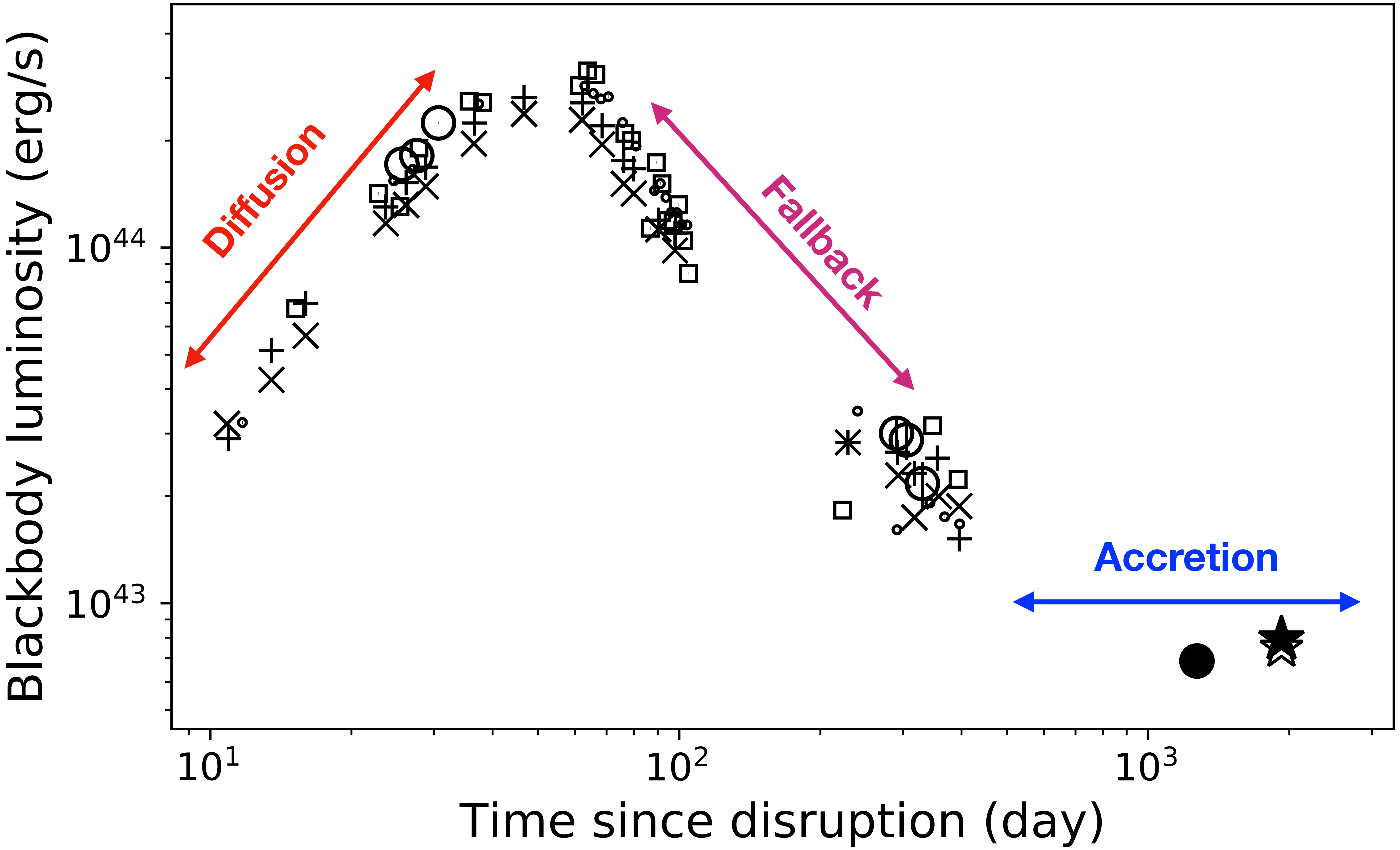
(Arcavi et al. 2014; French et al. 2016; Law-Smith et al. 2017; Graur et al. 2017)

Black hole mass and decay time



van Velzen, et al. (2021), review article

Summary of optical/UV emission

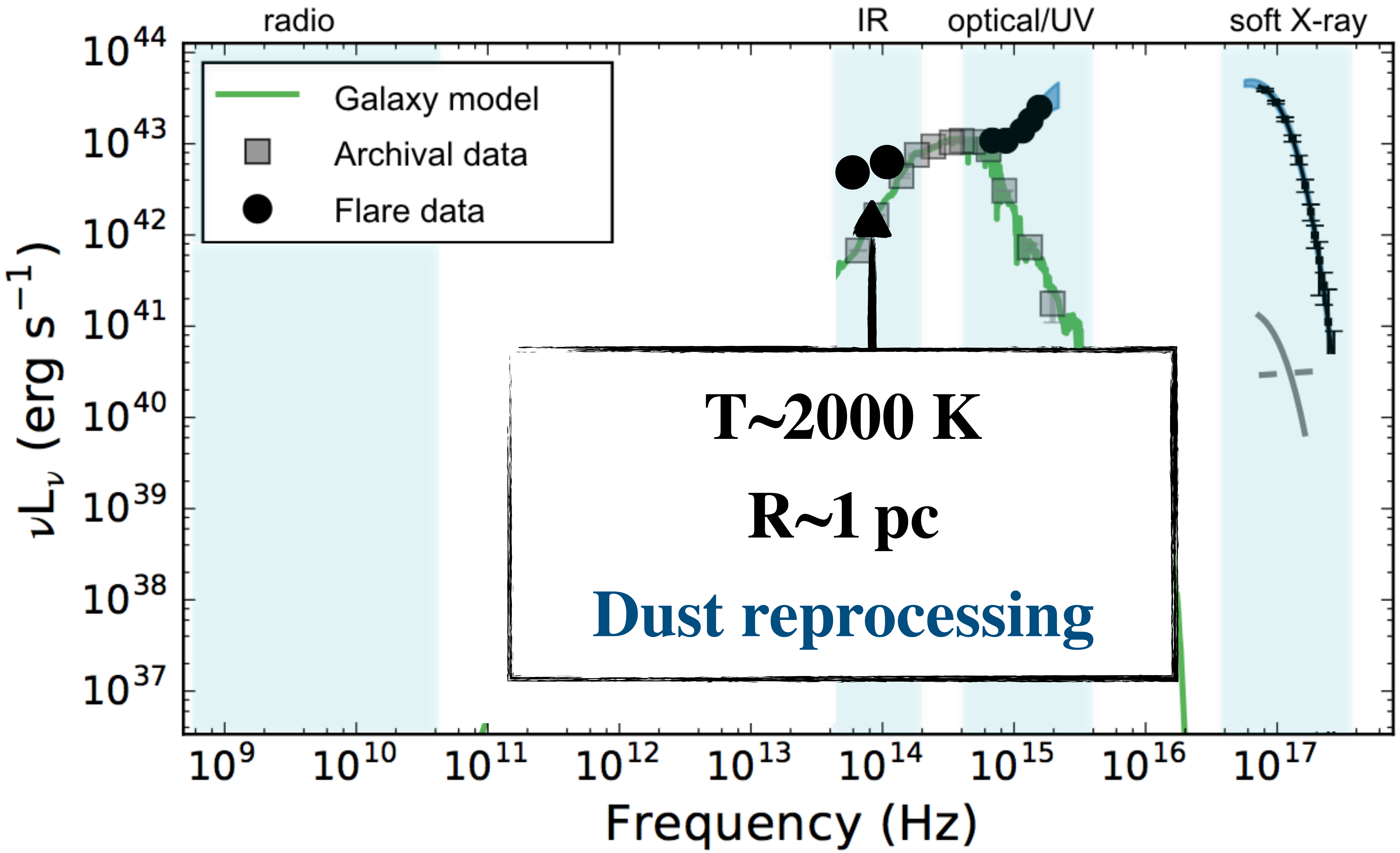


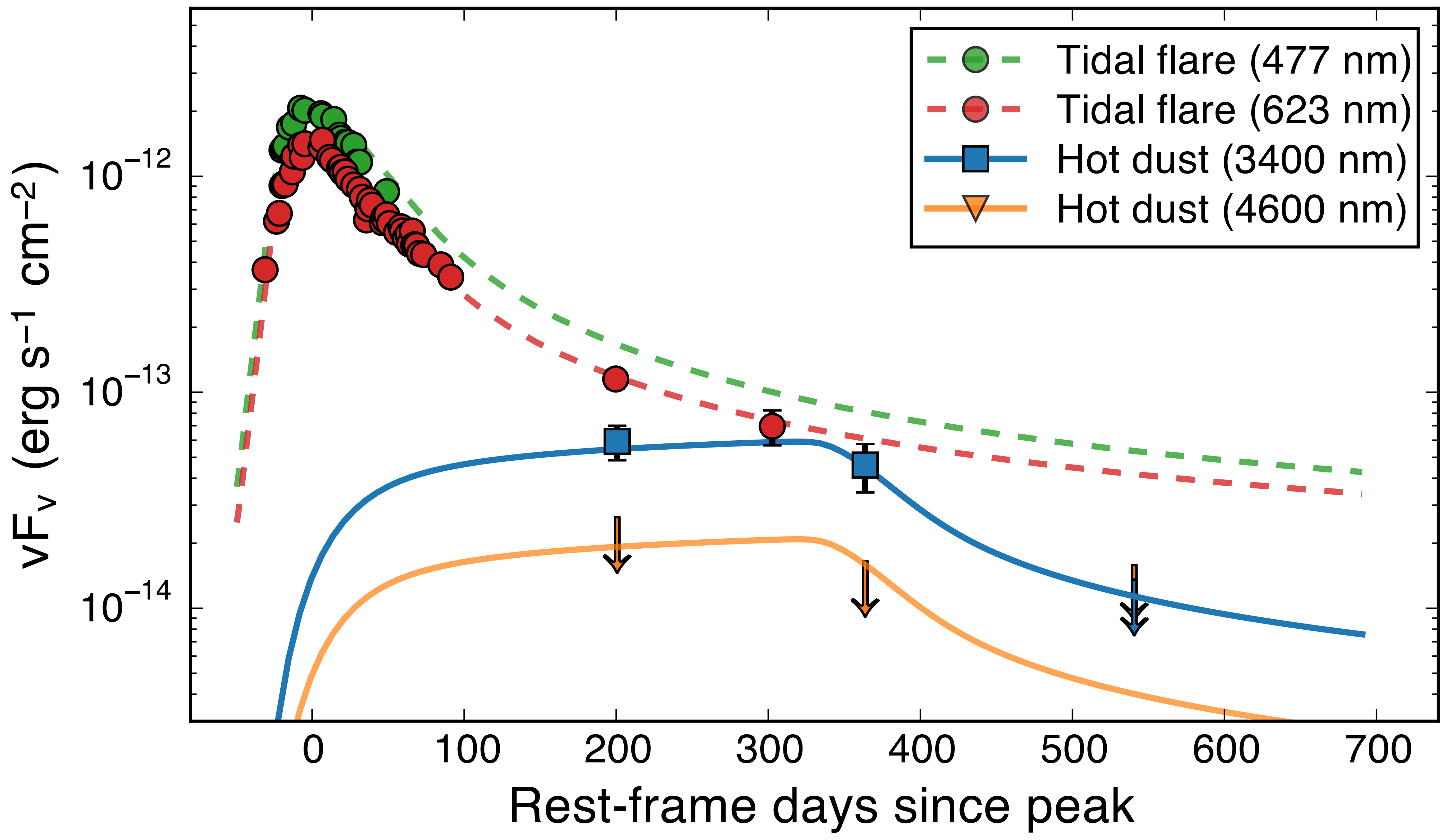
Information about:

- Density in photosphere; density of star(?)
- BH mass
- BH mass, stellar mass(?)

Data of PS-10jh Gezari et al. (2012, 2015); van Velzen et al. (2019)

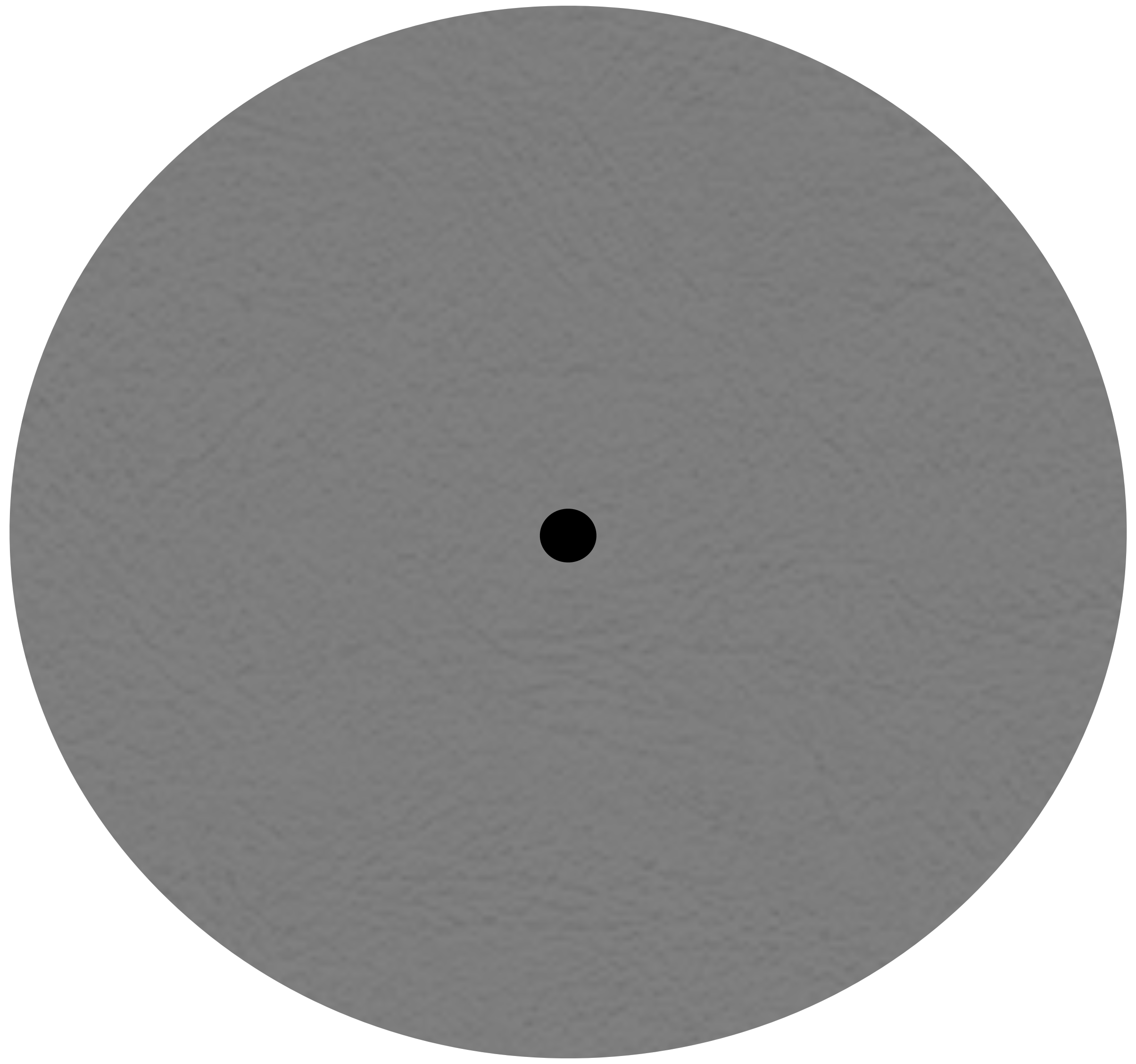
Spectrum of a tidal disruption flare





absorbed *TDE UV flux* = *IR emission*

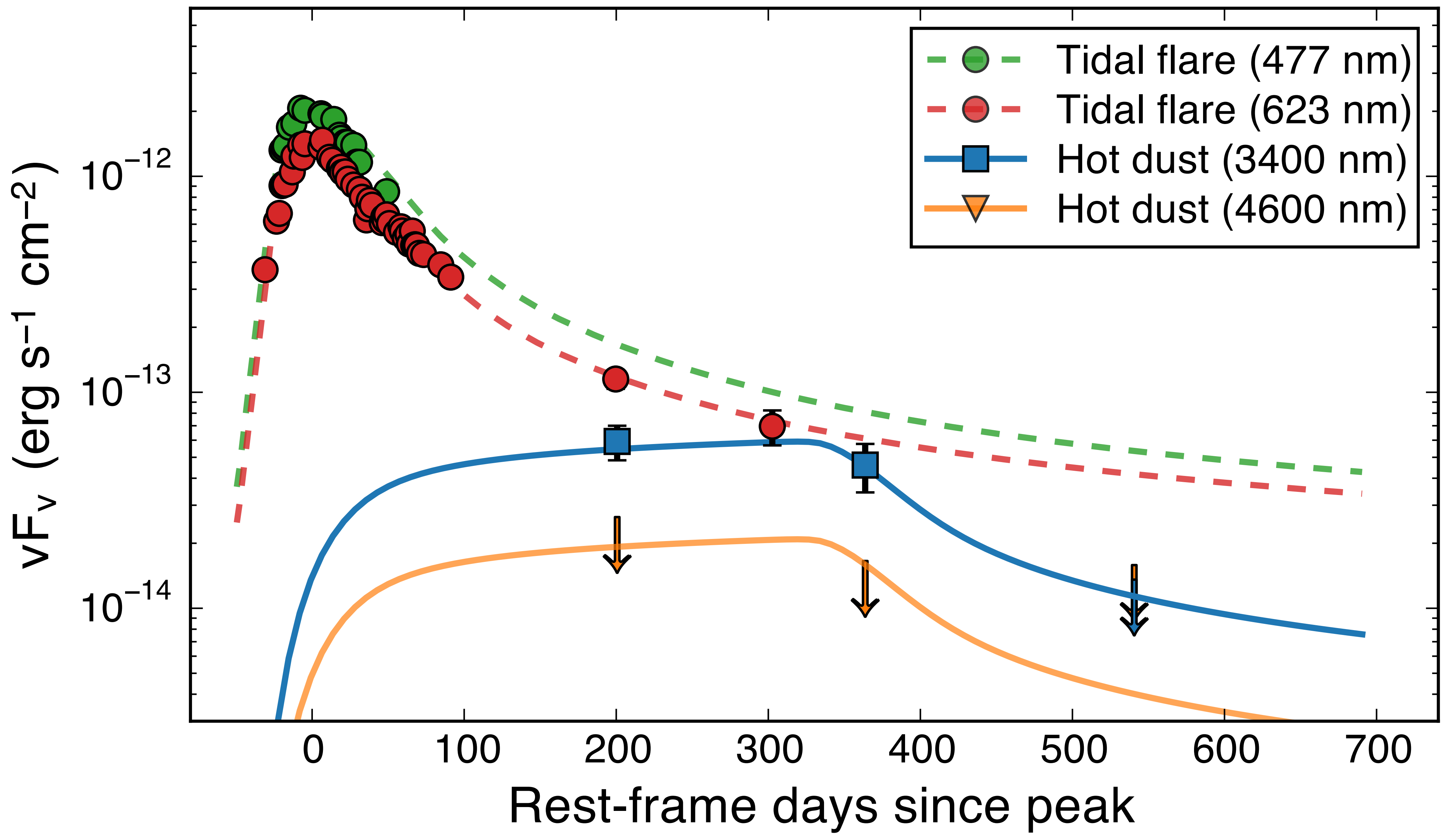
$$Q_{\rm UV}\,\frac{L_{\rm abs}a^2}{4R^2} = 4\pi a^2\, Q_{\rm IR}\sigma T_{\rm d}^4$$



- R ~ 0.1 pc
- L_{abs} ~ 10^{45} erg/s
- **Covering factor: L_{abs}/L_{dust} ~ 1%**

van Velzen et al. (2016); Lu et al. (2016); Jiang et al. (2016); Dou et al. (2016)

24



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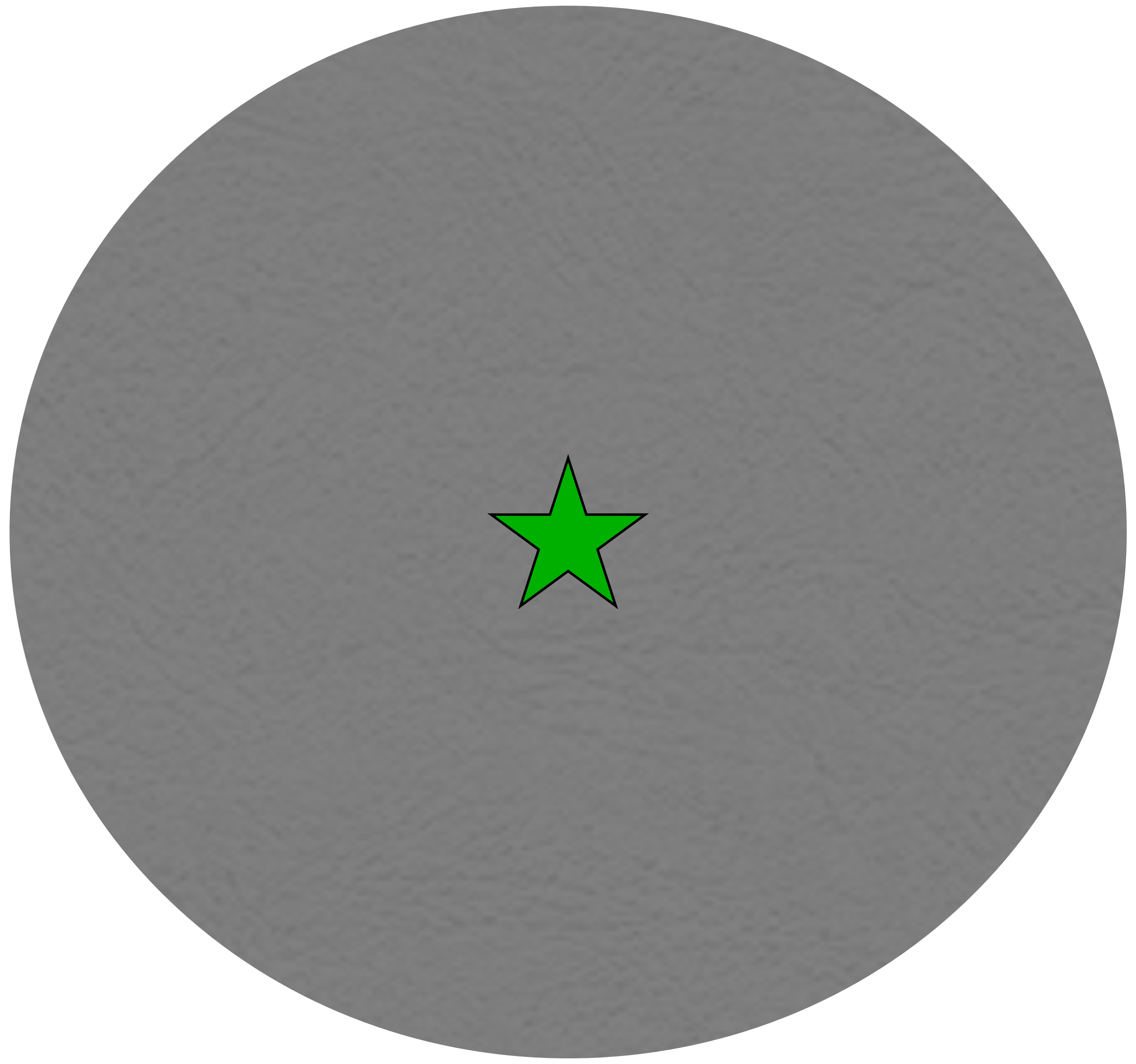

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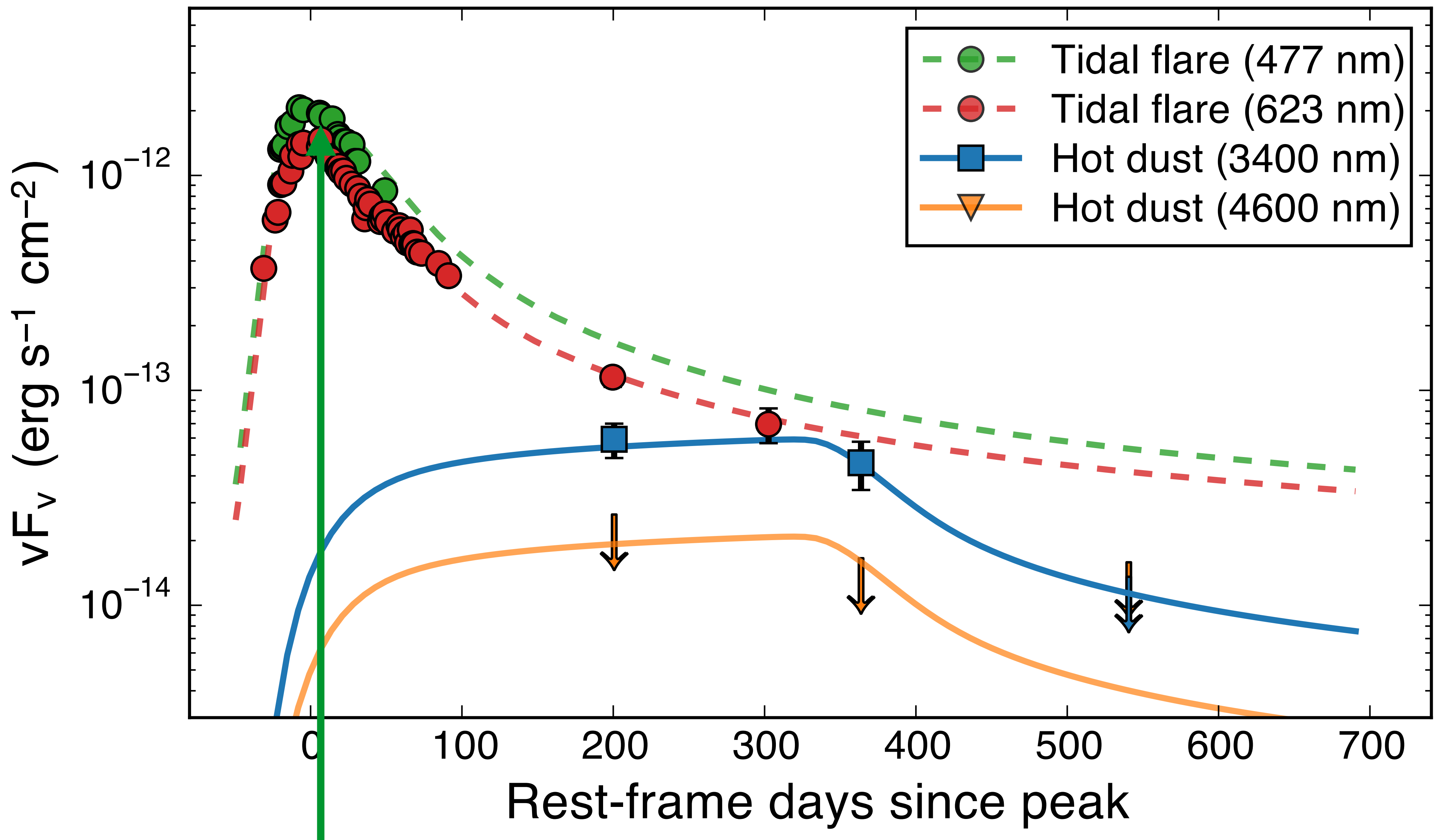

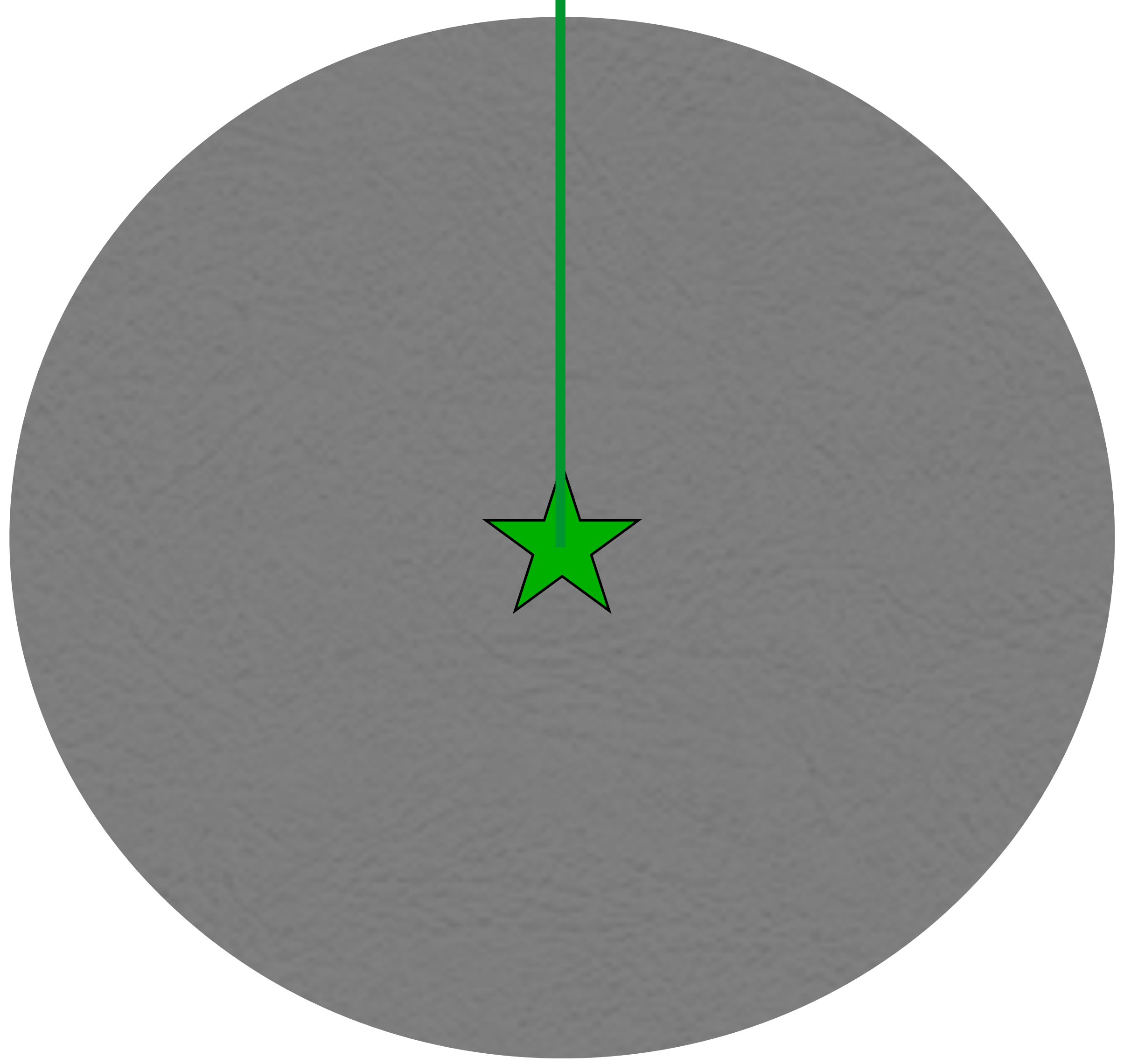

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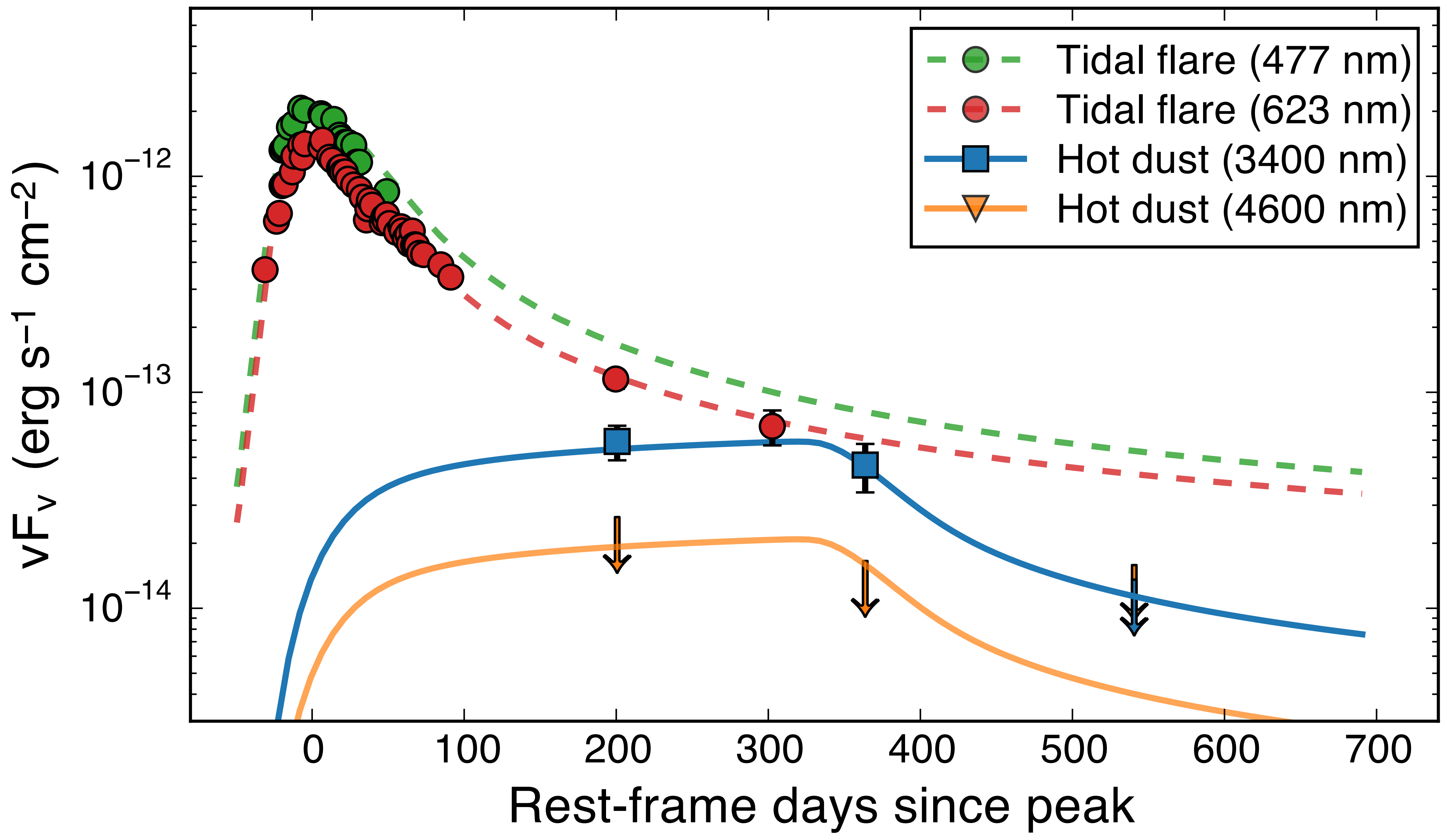

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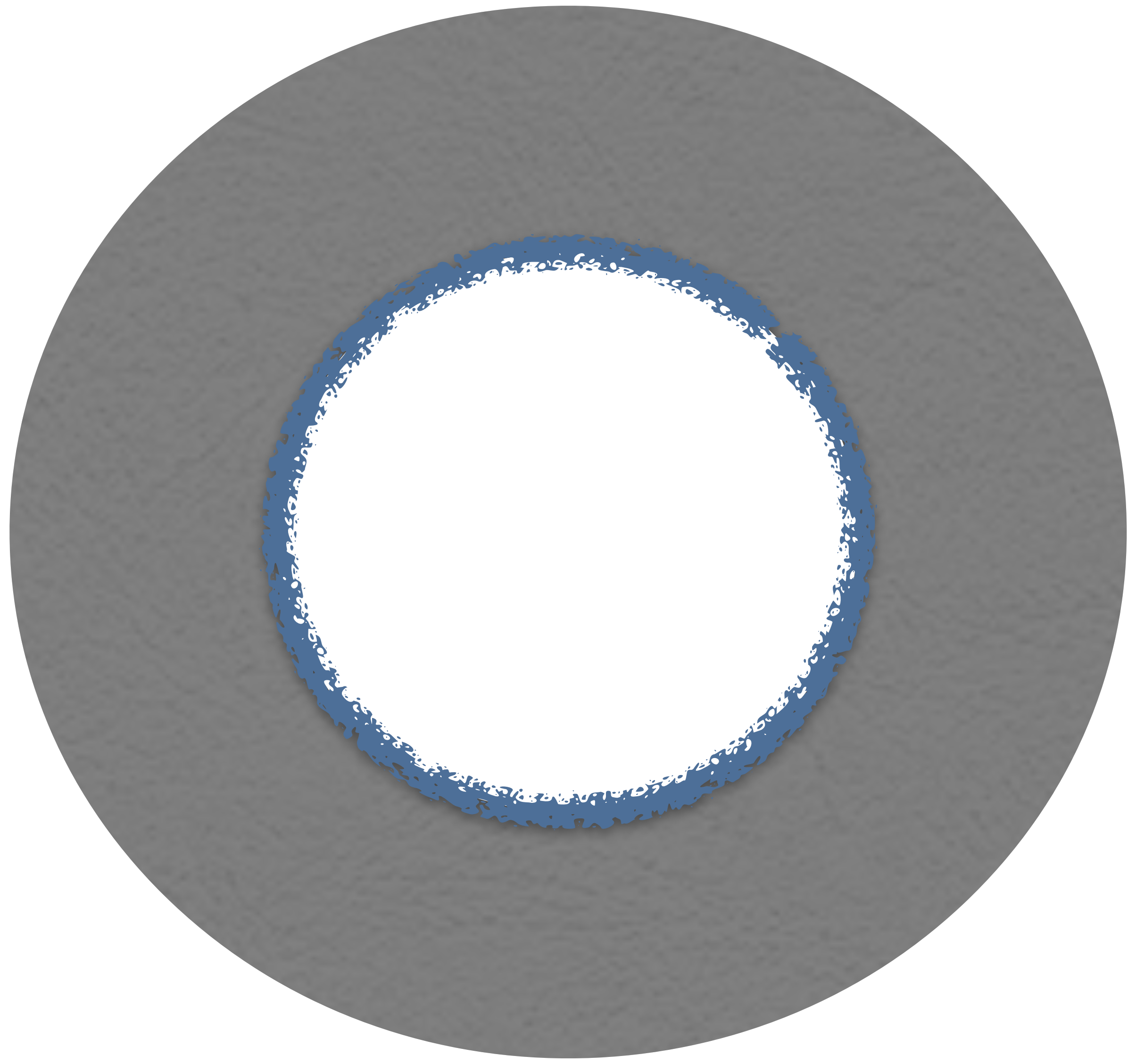

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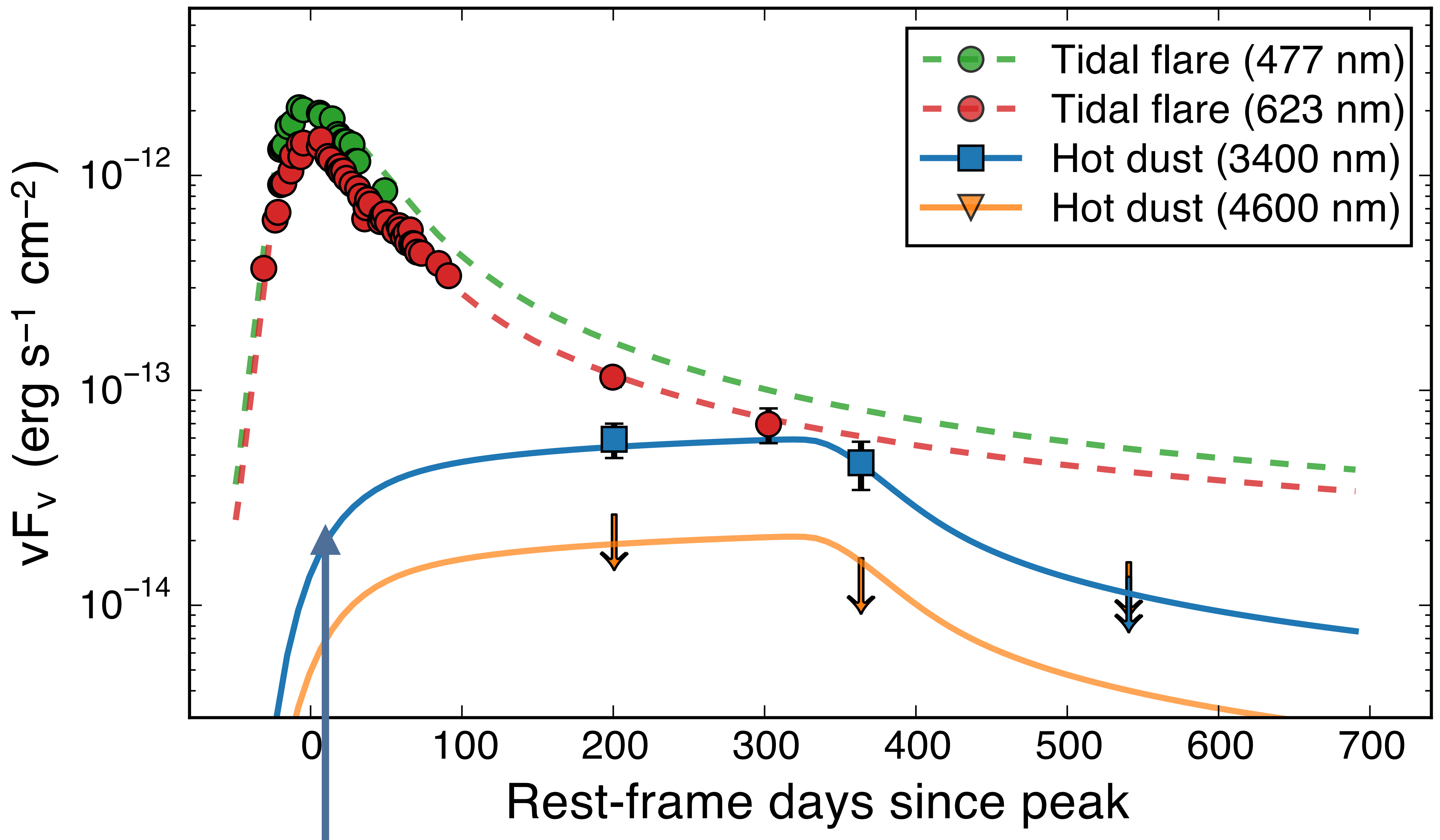

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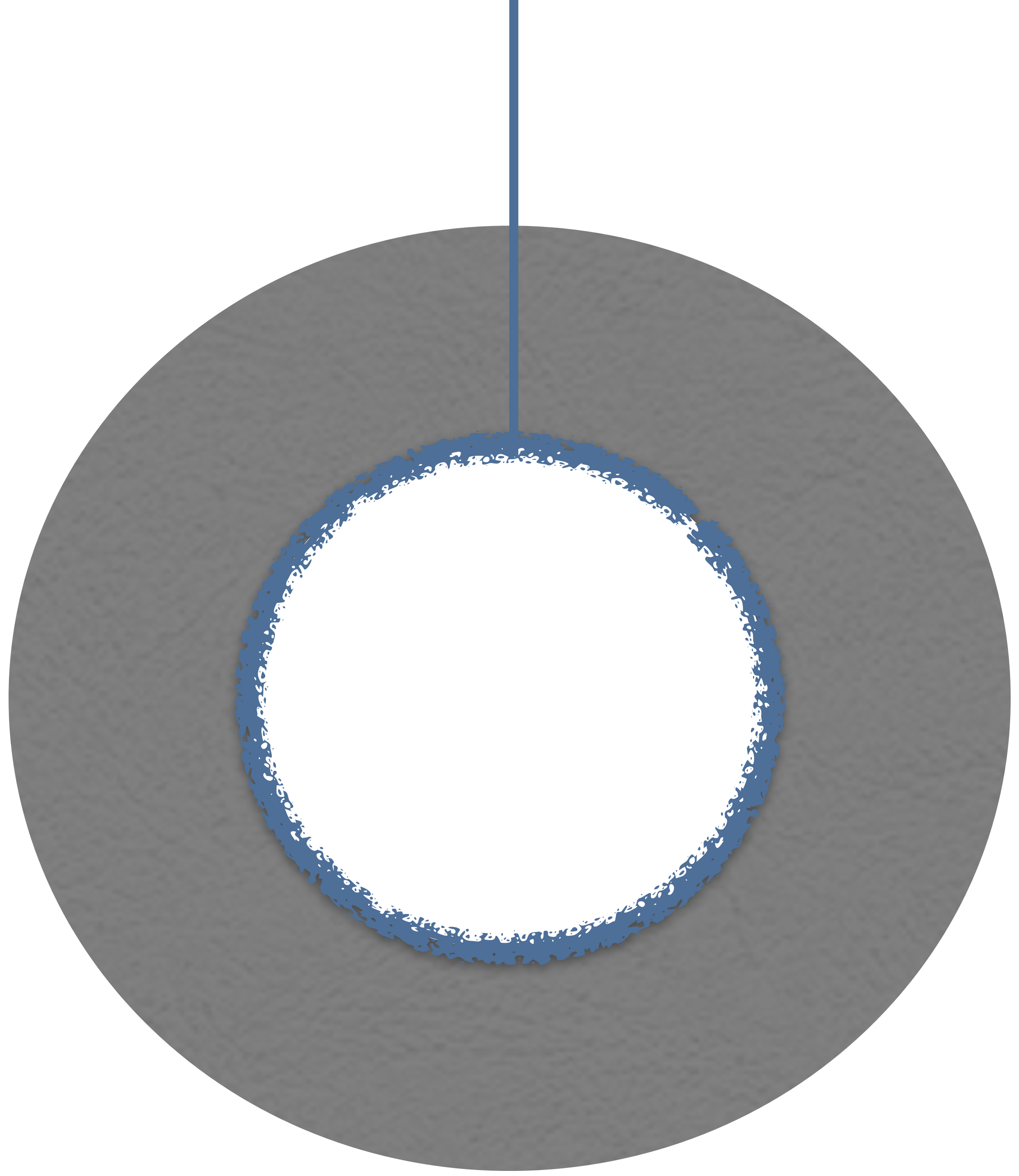

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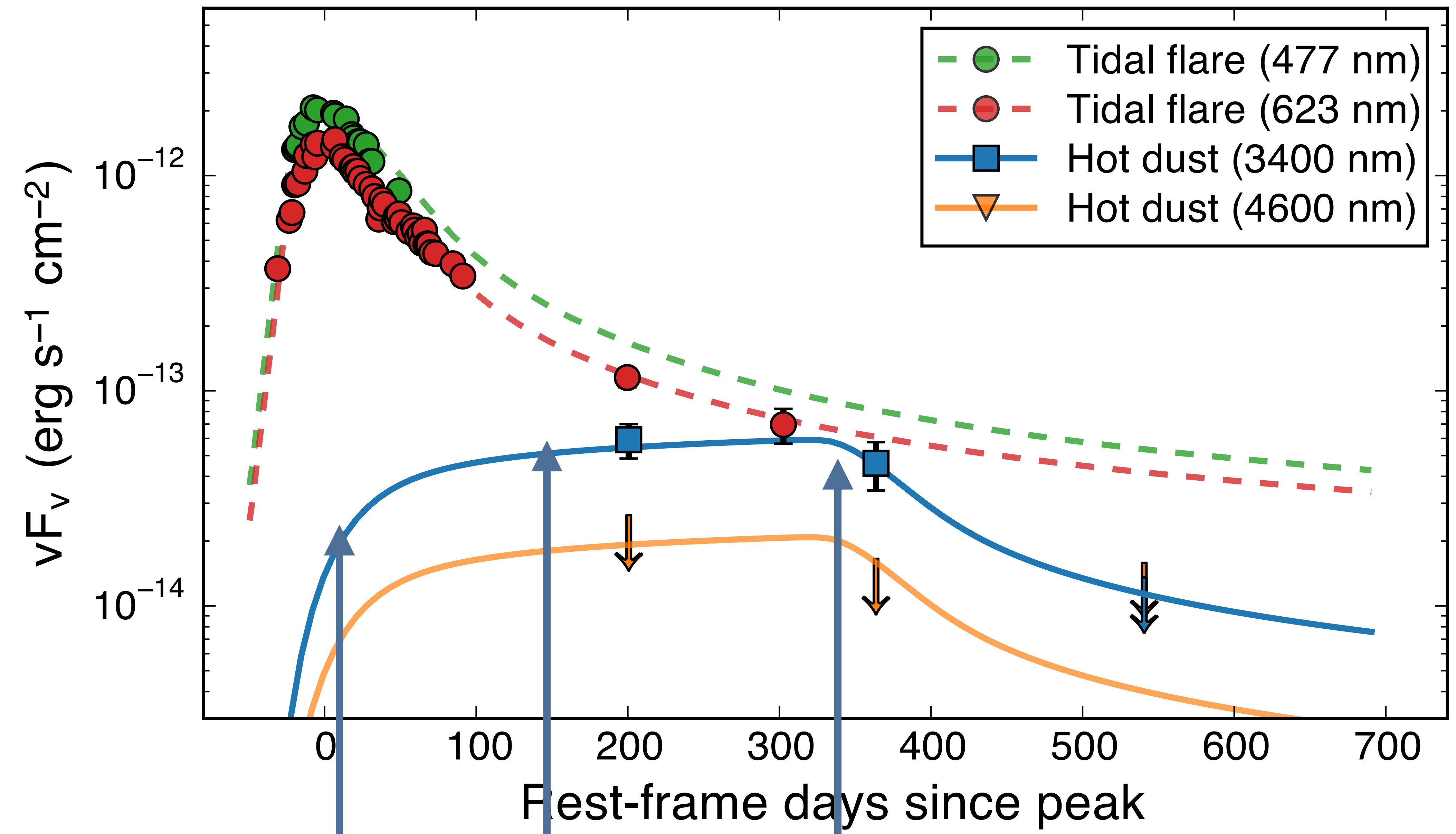

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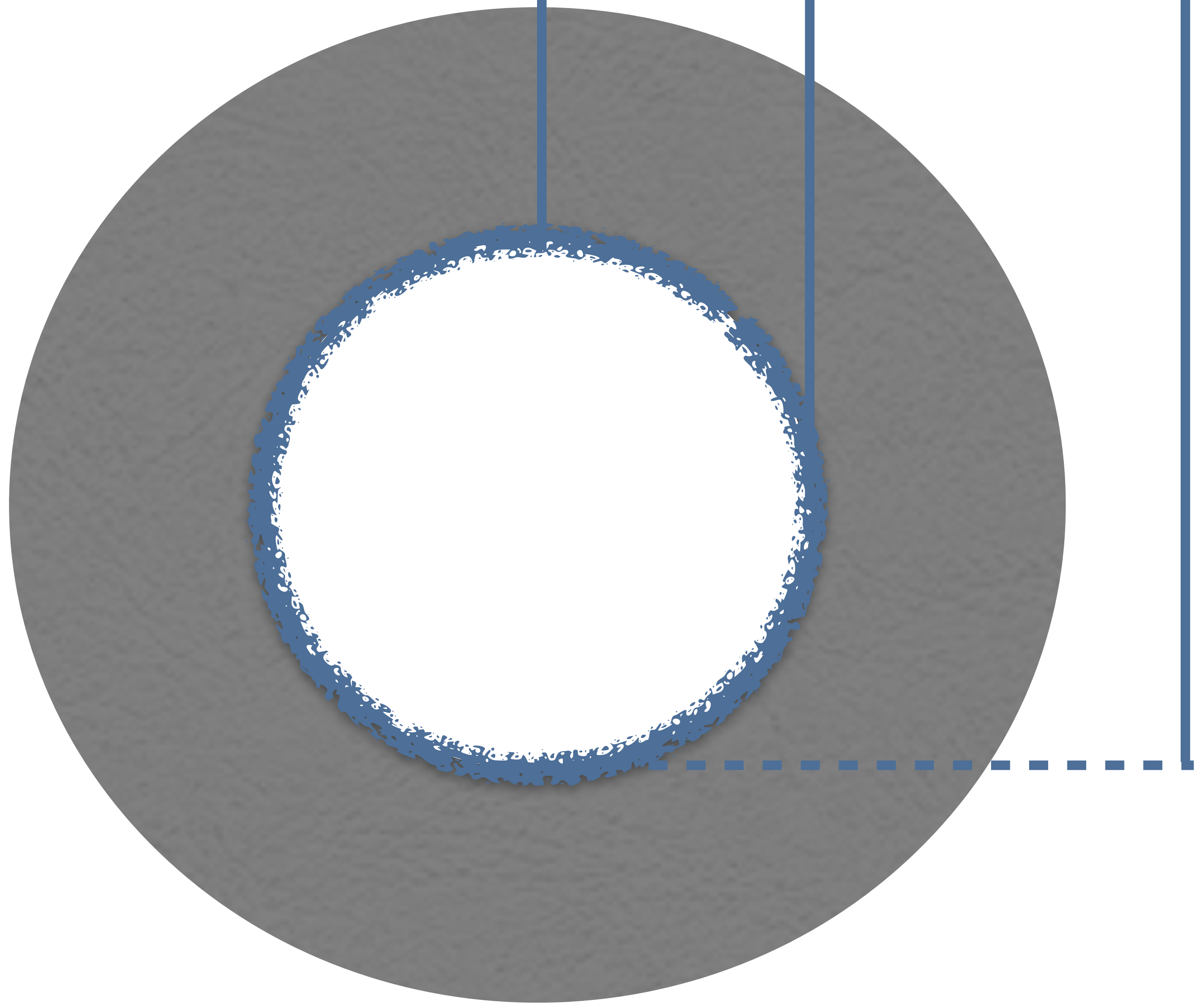

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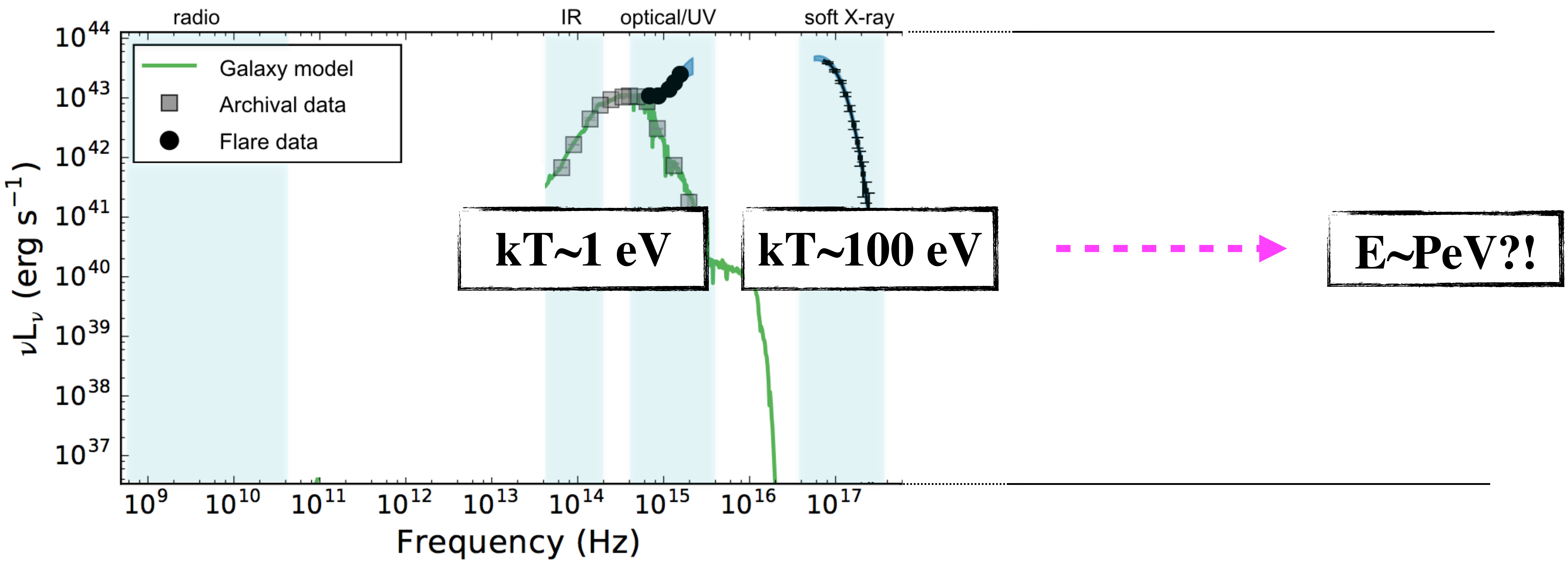
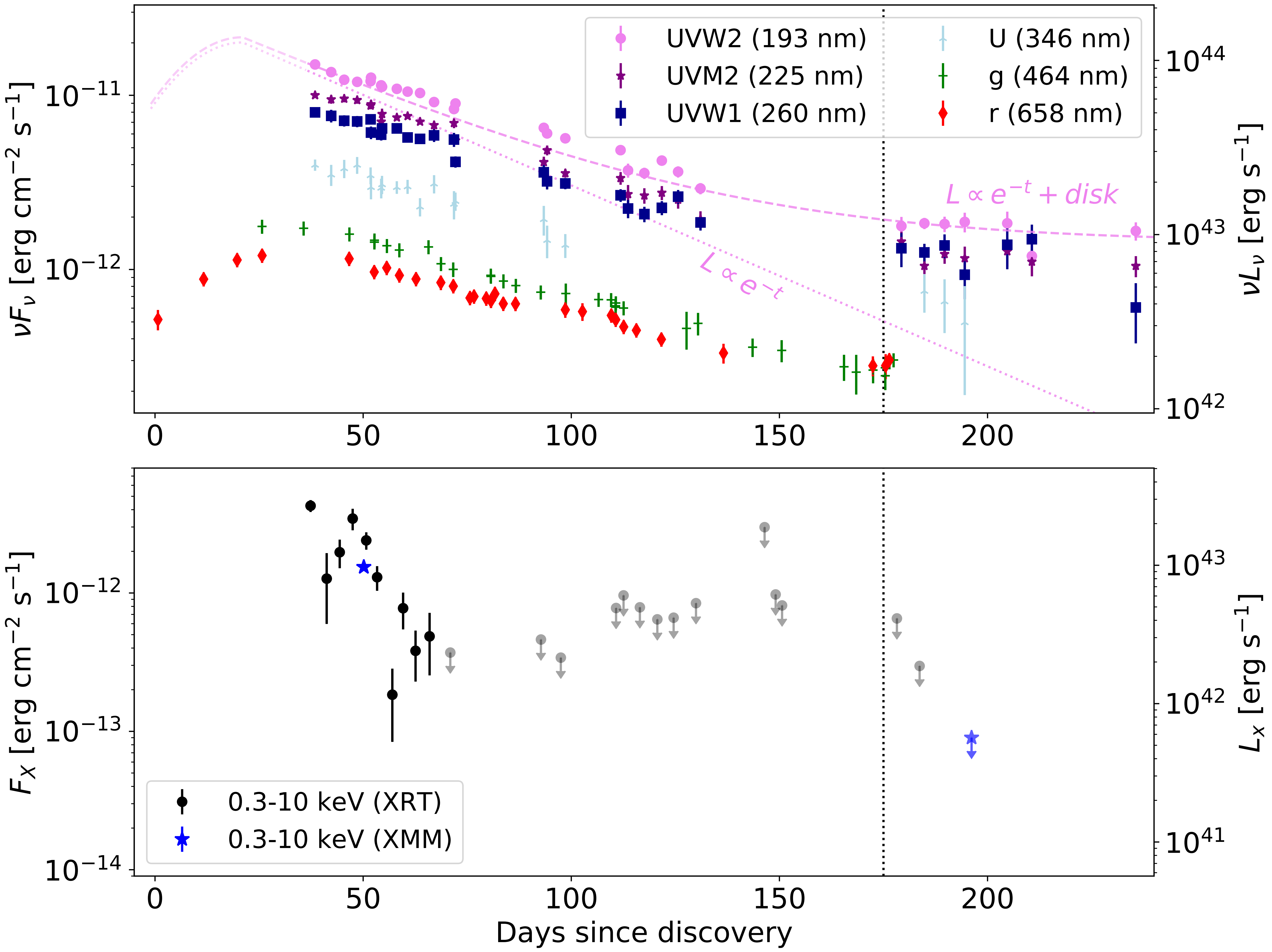
Multi-messenger astronomy



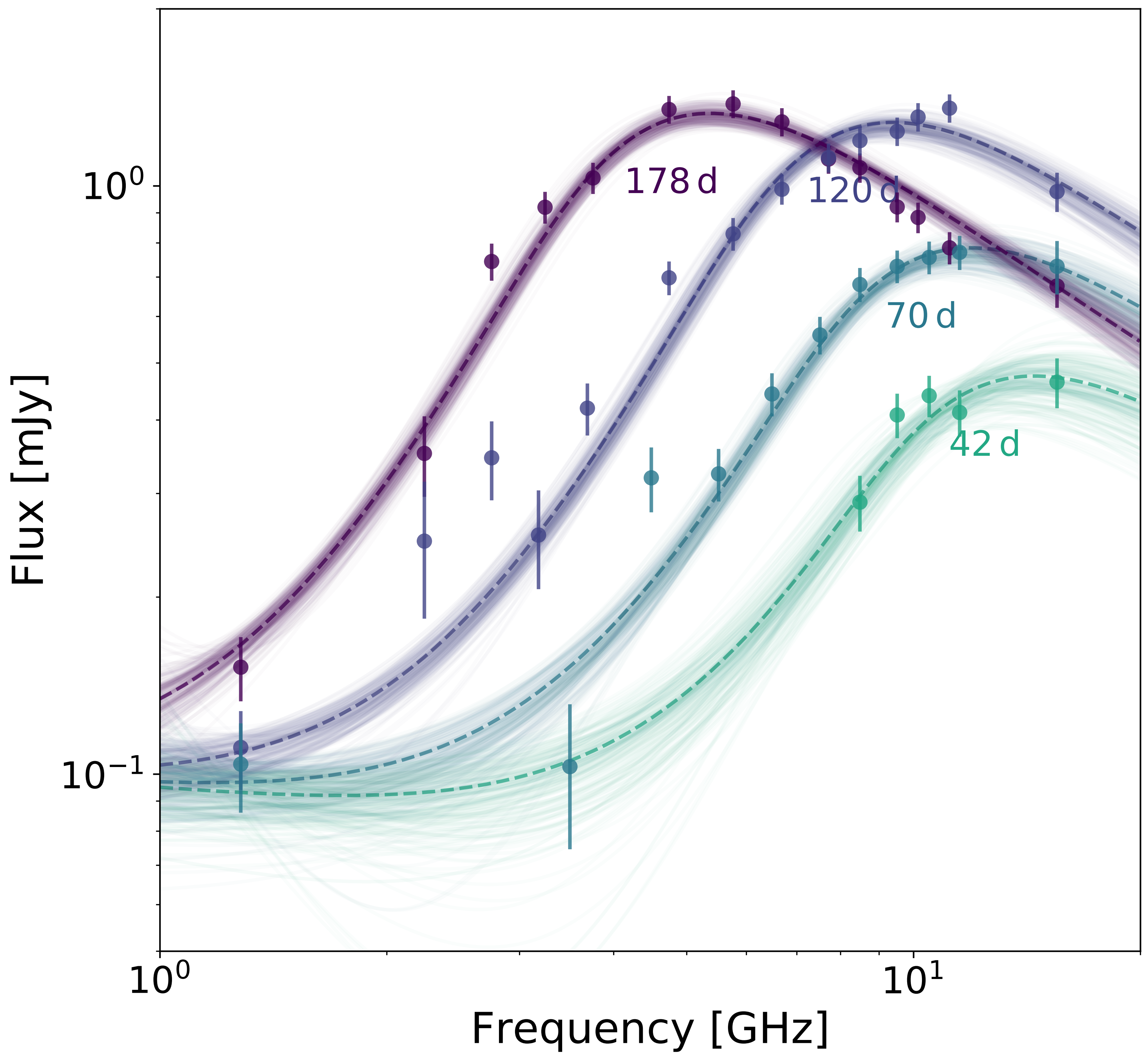
AT2019dsg: first TDE with a neutrino counterpart

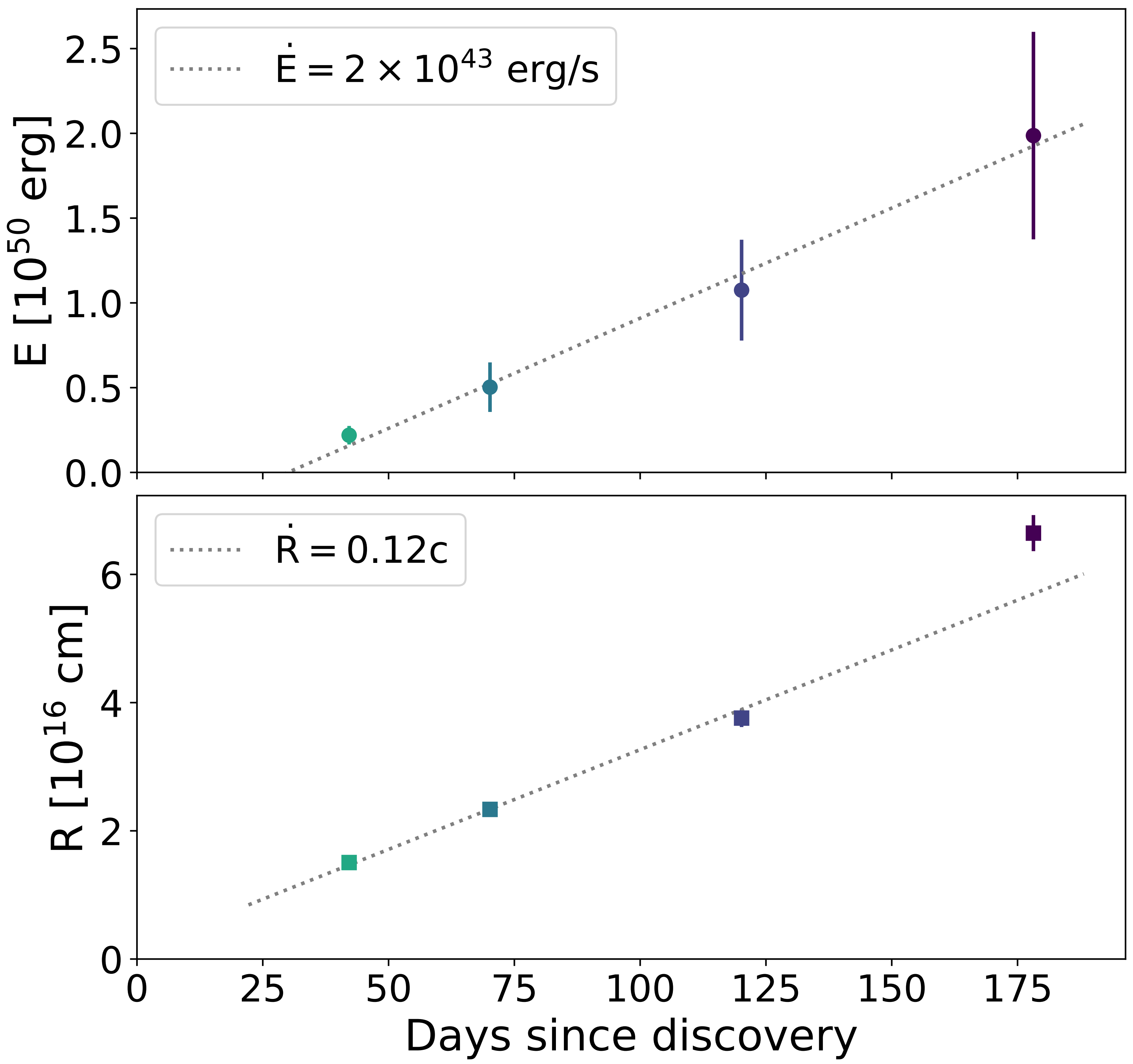
- Radio detected
- High UV luminosity (2nd highest flux on Earth)
- p=0.005 for change coincidence
- Neutrino arrived late, about 6 months post peak



Radio monitoring with the VLA

Constant energy injection by central engine

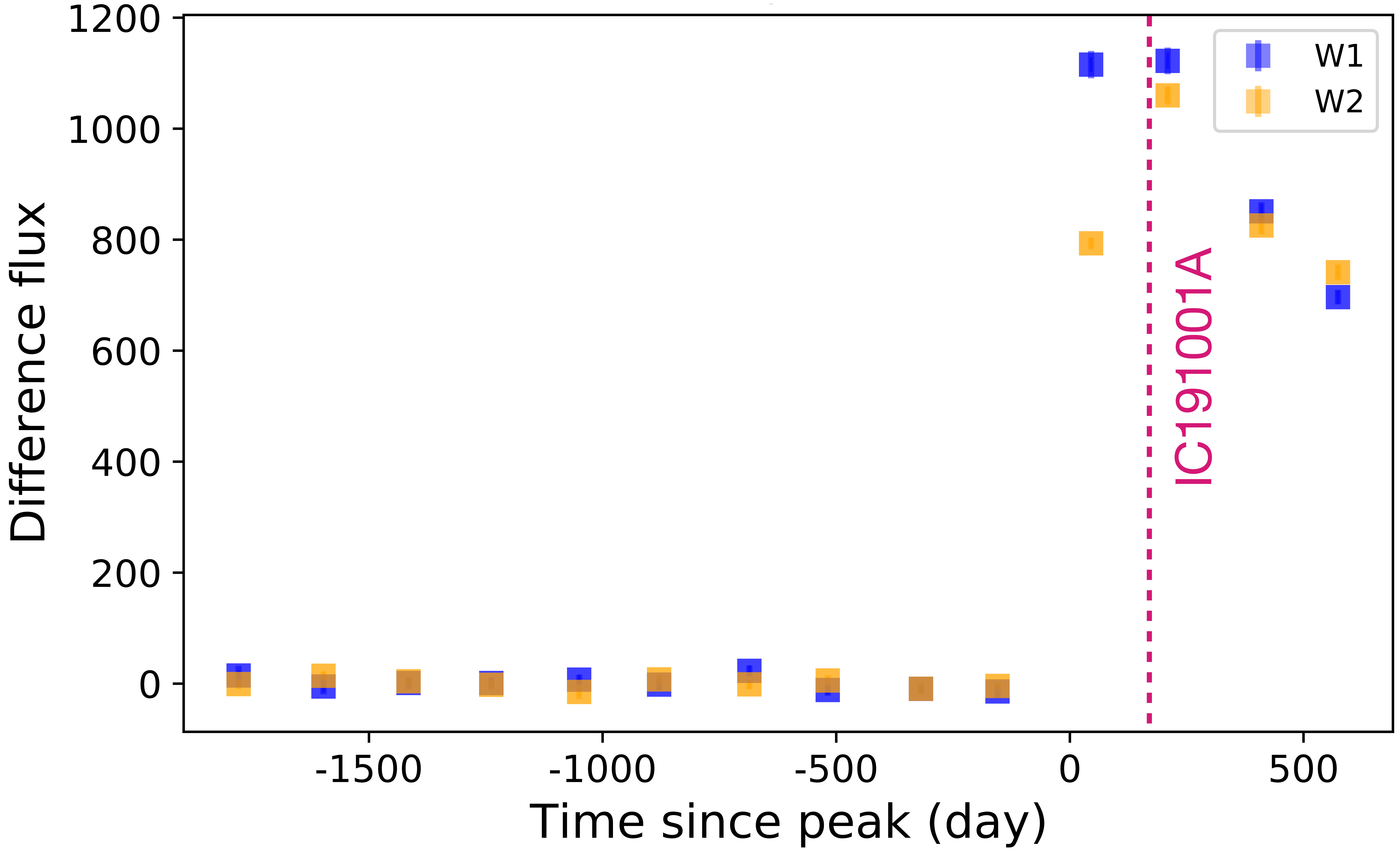




Stein, van Velzen et al. (2021, Nature Astronomy)

AT2019dsg: record-breaking dust echo

Strongest of all ZTF transients (TDEs and AGN)



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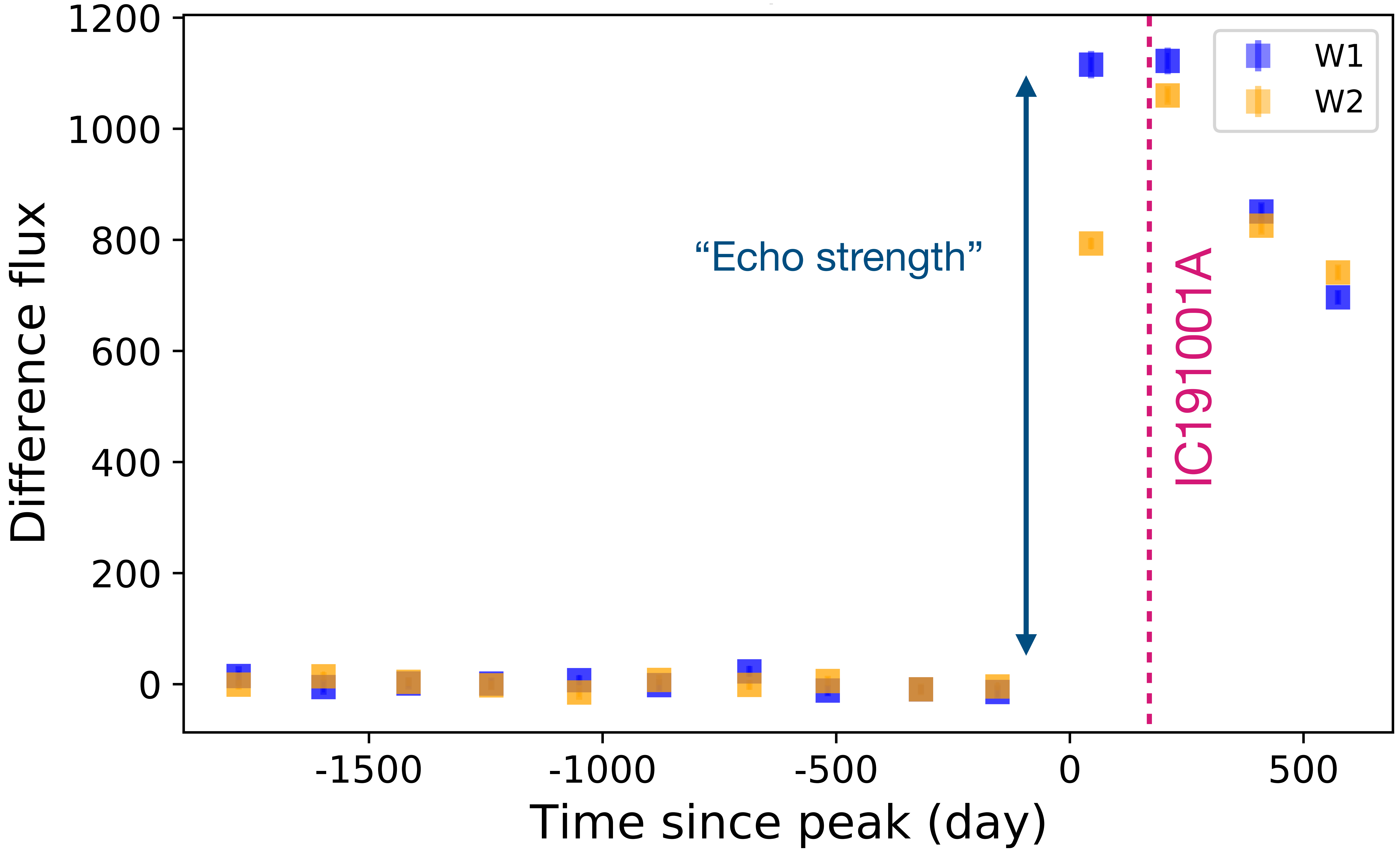
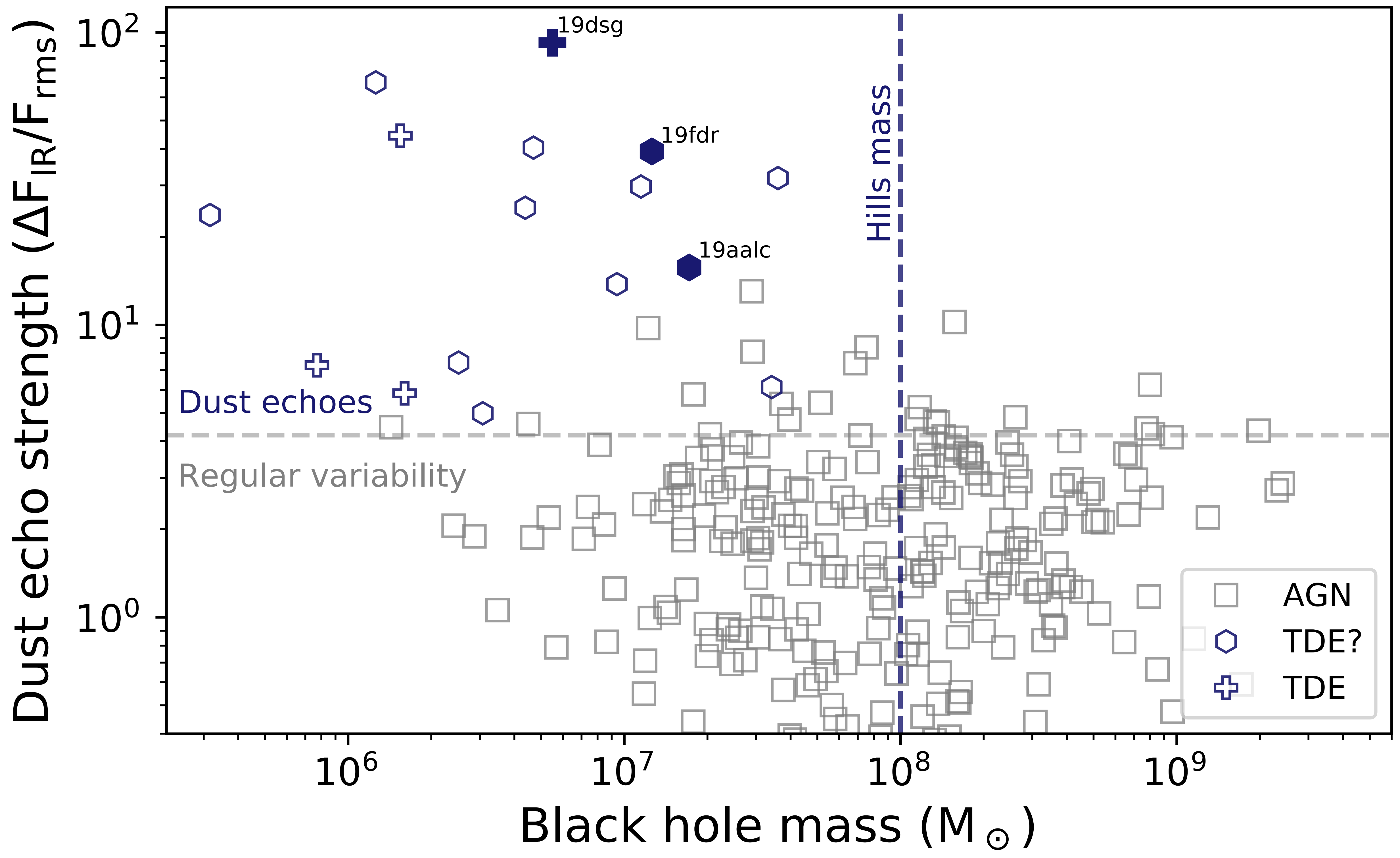


Systematic search for neutrinos from dust echoes

- Collect all infrared dust echoes
- Unifies TDEs and AGN flares
- Results:
    - Large echoes exclusively from low-mass black holes



van Velzen, Stein, et al.
(under review; arXiv:2111.09391)

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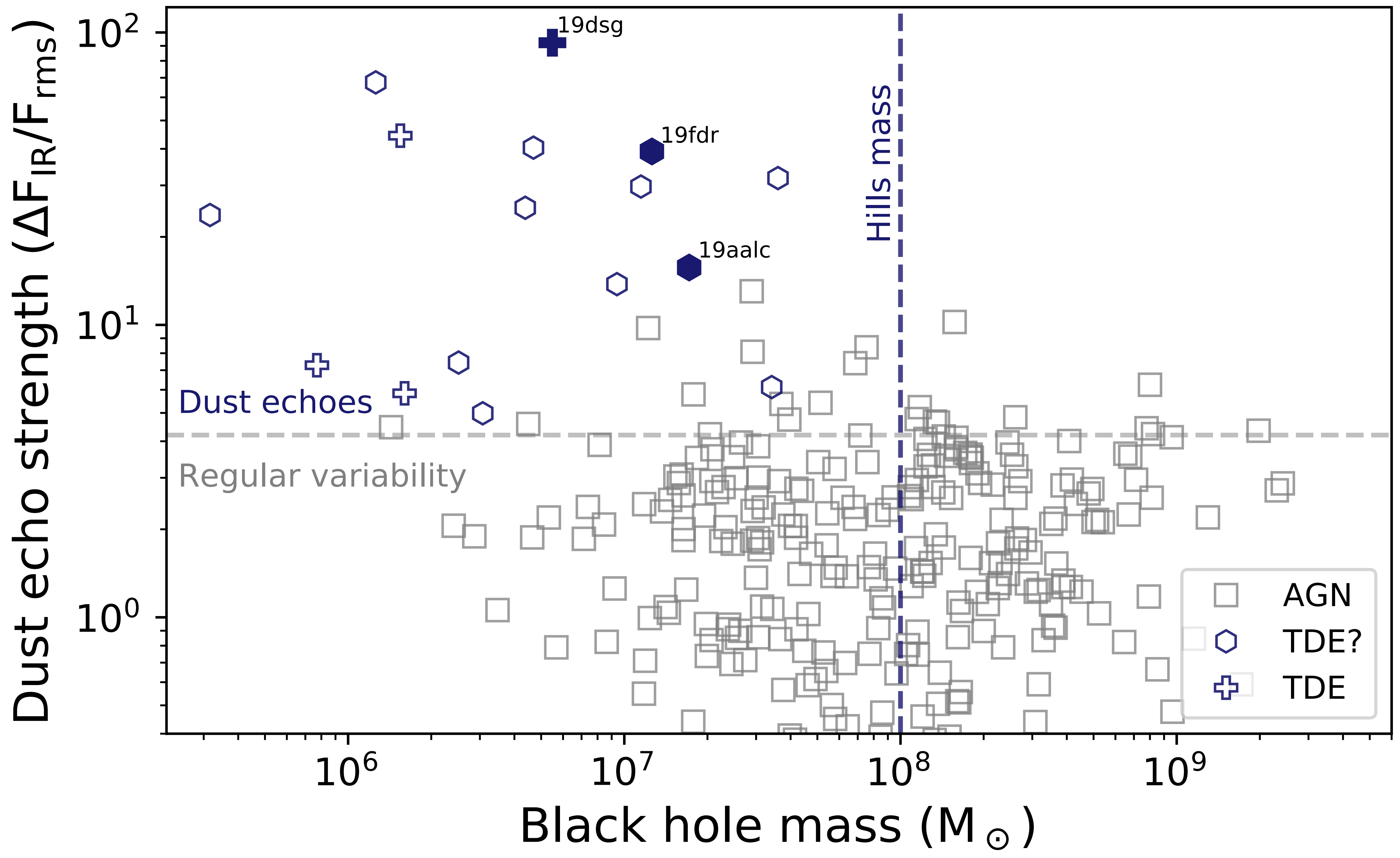

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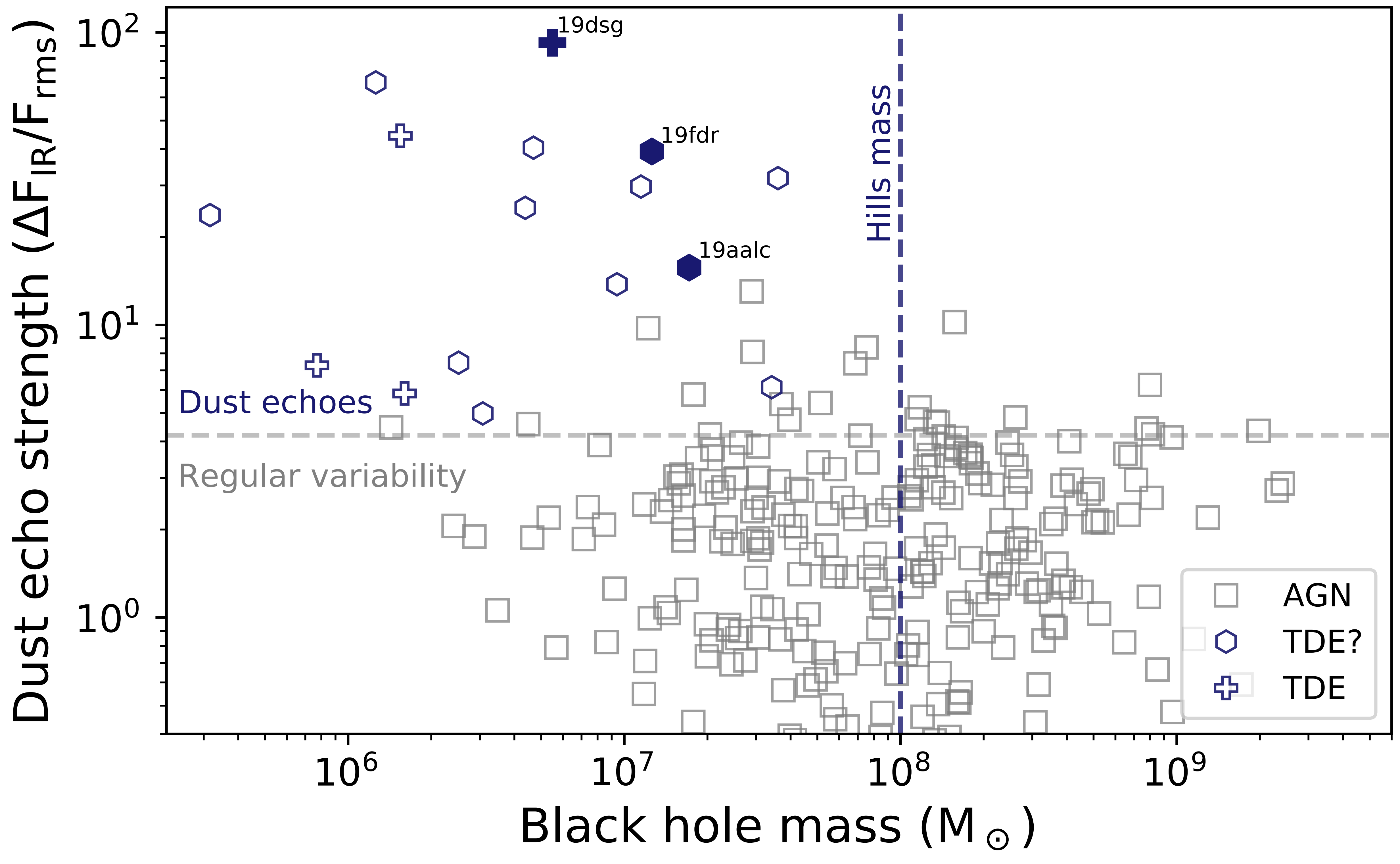
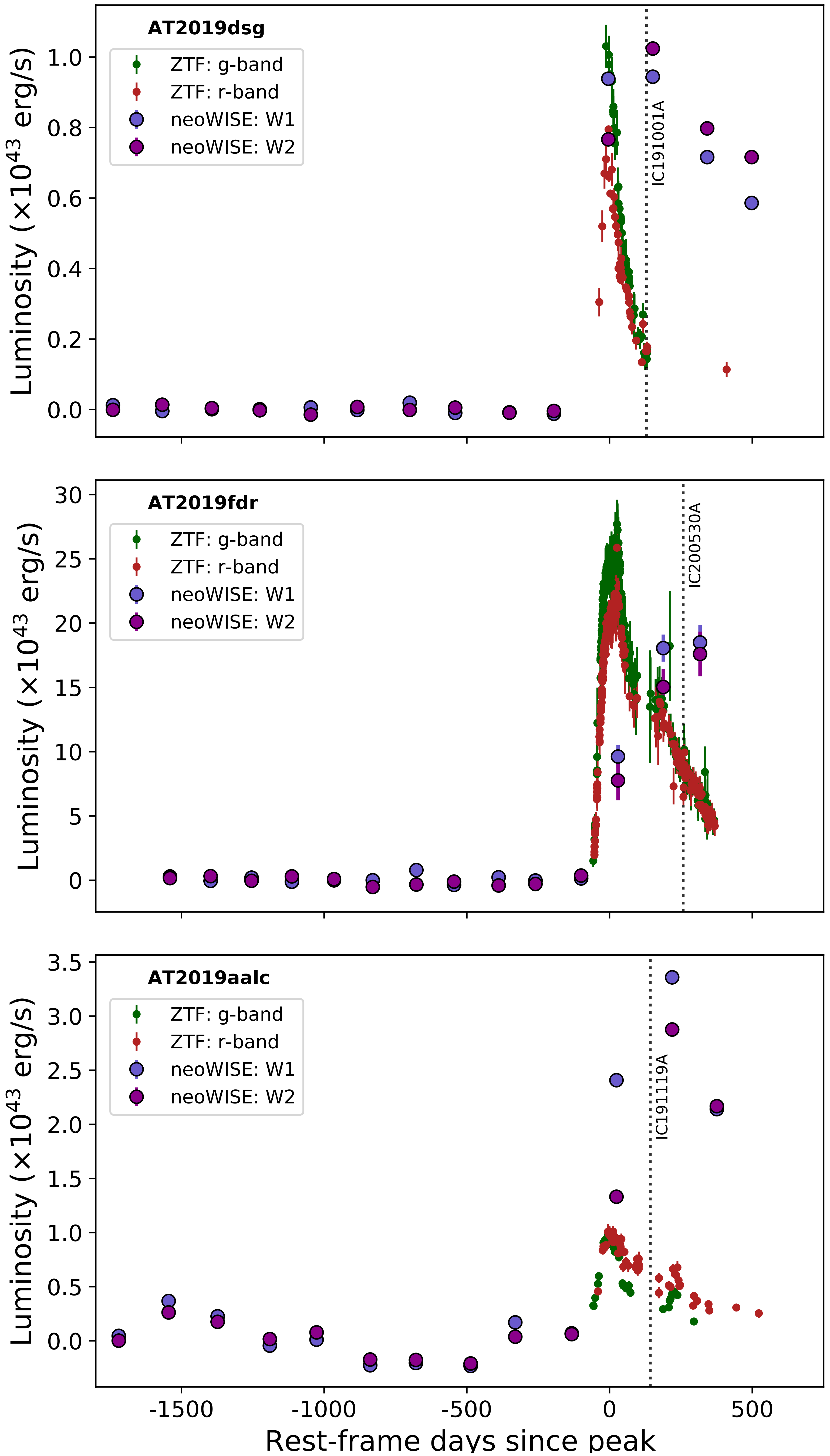
  - **Three** events coincident with IceCube alerts
  - p~10^{-4} = 3.6 sigma



van Velzen, Stein, et al.
(under review; arXiv:2111.09391)

Consistent multi-wavelength picture

- AT2019dsg: strongest dust echo in ZTF
- AT2019aalc: highest IR echo flux in ZTF



van Velzen, Stein, et al. (arXiv:2111.09391)

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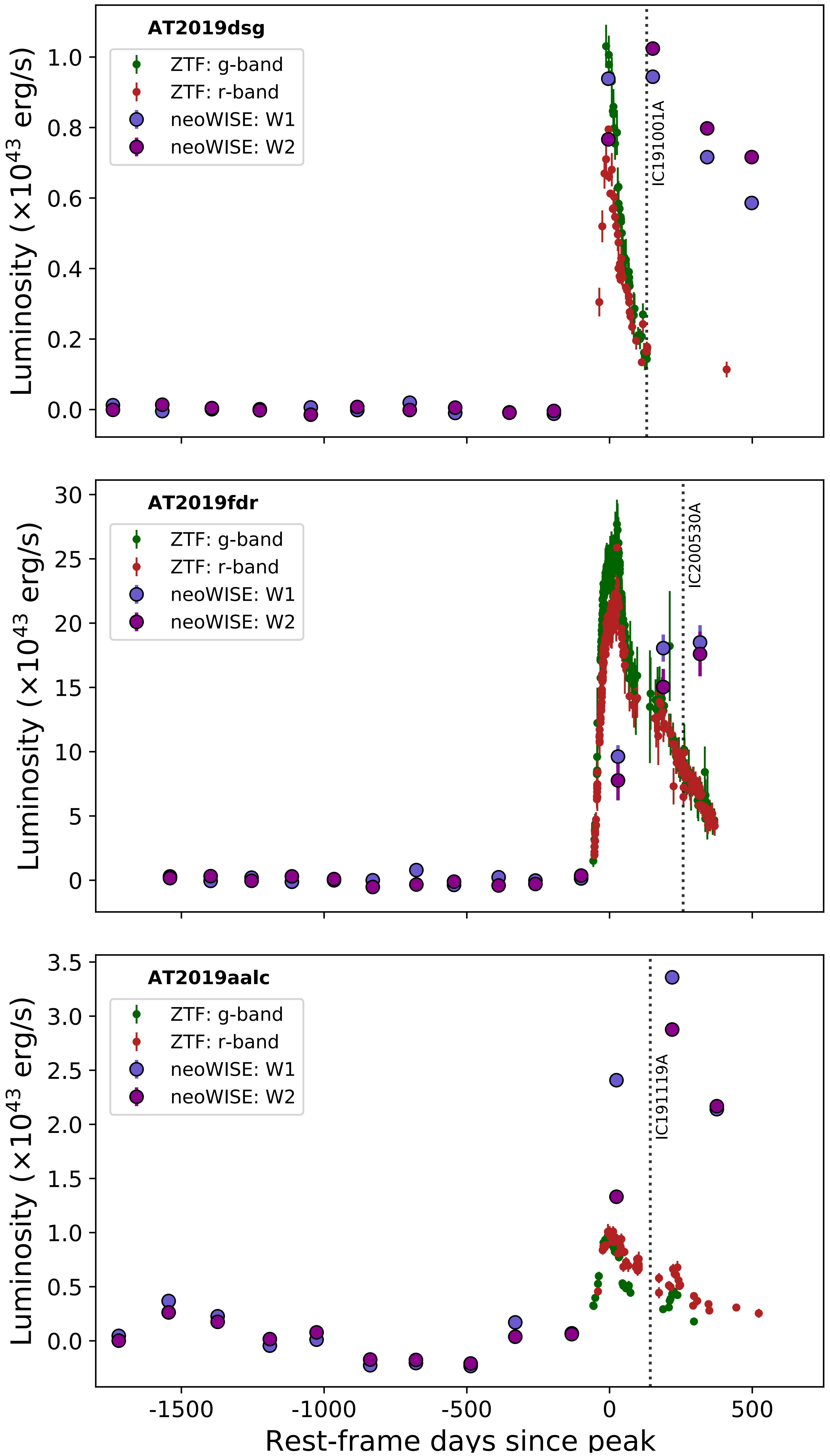
- **All three** neutrino associations:



van Velzen, Stein, et al. (arXiv:2111.09391)

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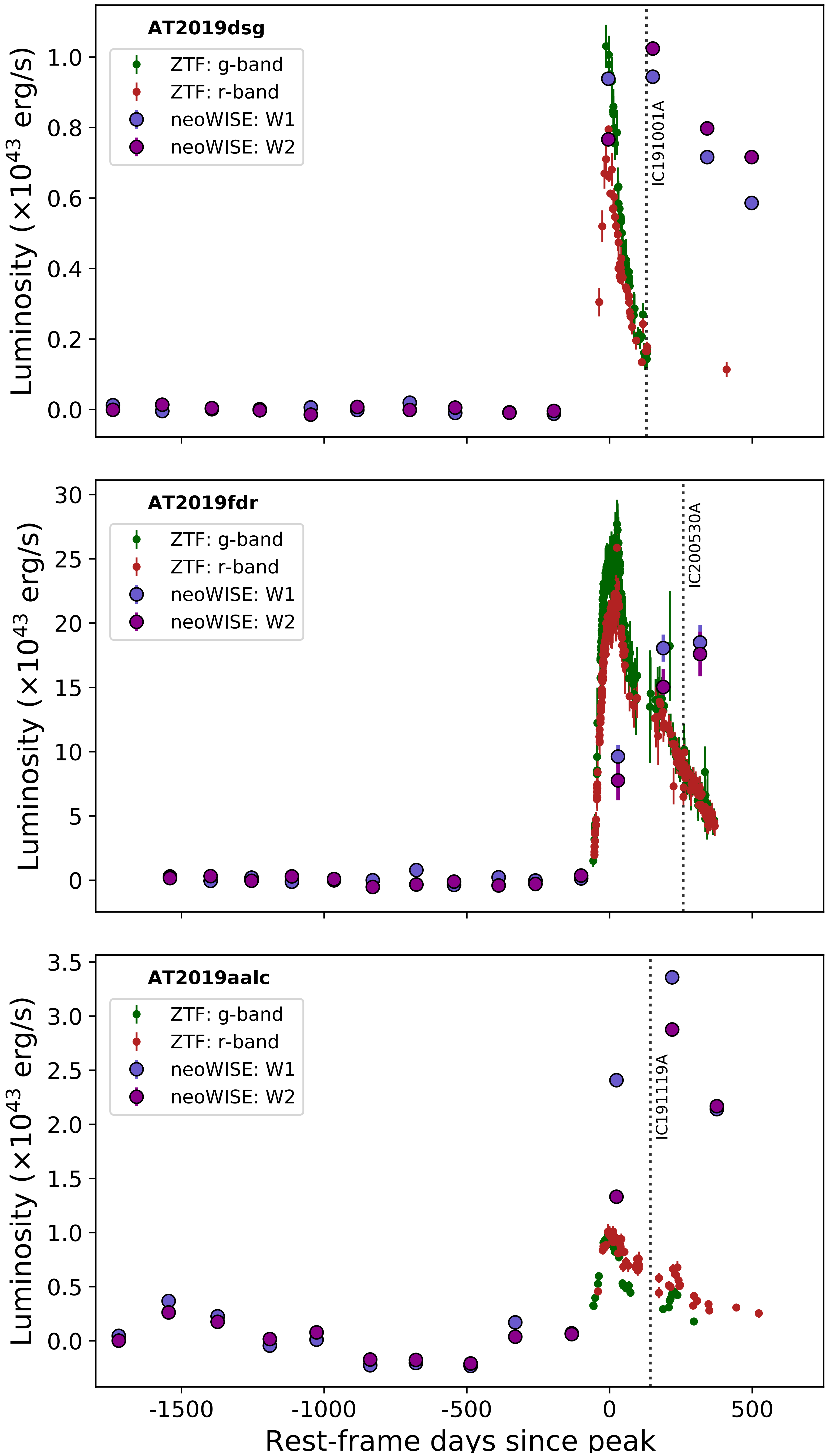
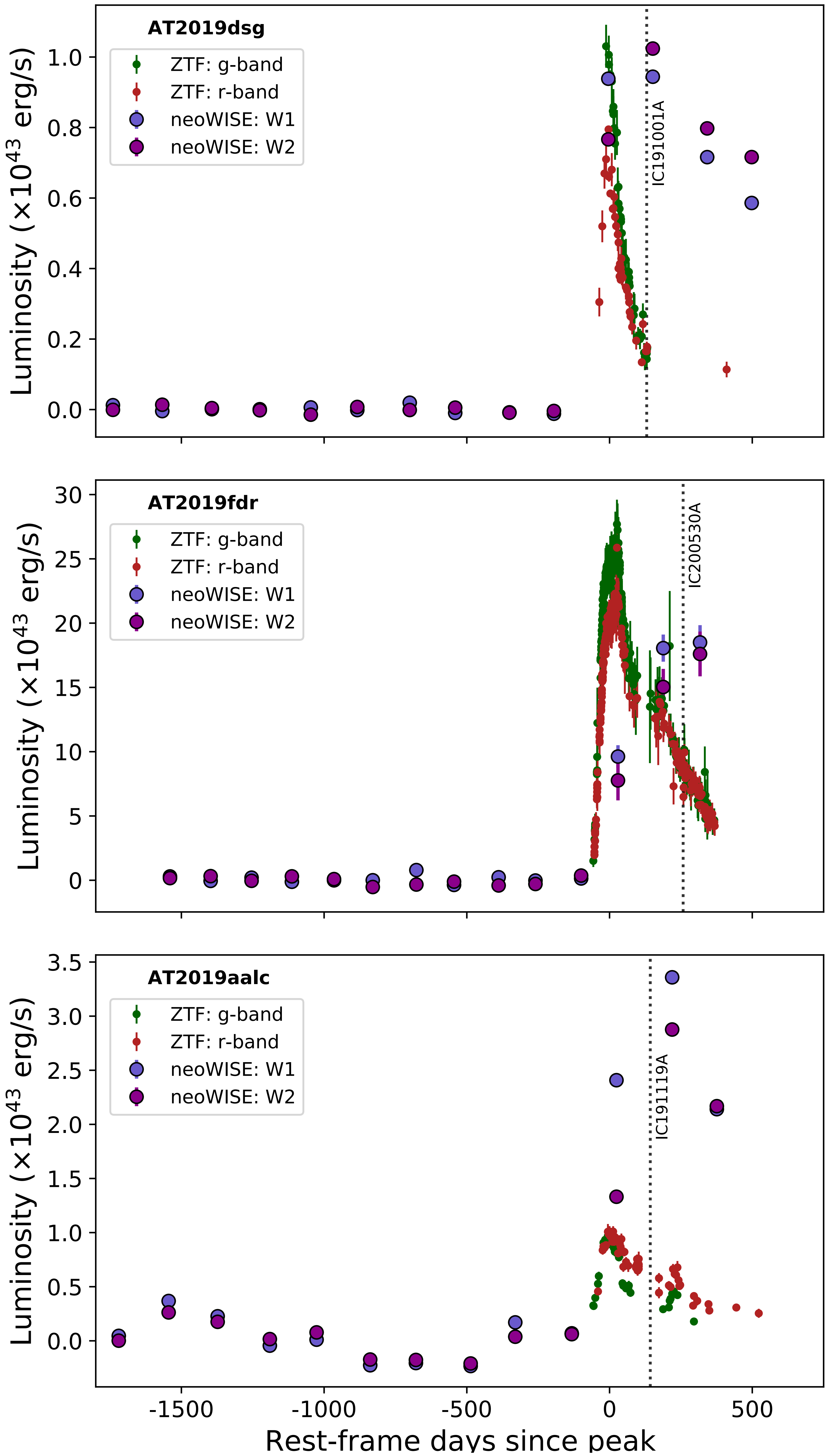


van Velzen, Stein, et al. (arXiv:2111.09391)

Consistent multi-wavelength picture

- AT2019dsg: strongest dust echo in ZTF
- AT2019aalc: highest IR echo flux in ZTF
- **All three** neutrino associations:
    - Detected in the radio (uncommon for AGN)
    - Detected in X-ray, with soft spectra (very uncommon for AGN)



van Velzen, Stein, et al. (arXiv:2111.09391)

Summary: what can TDEs do for you?

- **Large samples:** measure black hole spin, black hole occupation
- **Monitoring X-ray/radio:** measure spin (QPOs) and accretion physics
- **Neutrino detections:** learn about PeV-scale particle acceleration
- Could produce detectable mHz **GW** emission (Stone et al. 2013; Toscani et al. 2020; Pfister et al. 2021)

What is next?

- More neutrinos: KM3NET, IceCube-Gen2
- More TDEs with Rubin Observatory: 10-1000 per year
- More detections in (blind) radio surveys: VLASS, DSA-1000, ngVLA, SKA
- Optical/UV detections from space: Gaia, EUCLID, ULTRASAT, Roman
- More IR detections: ground based, JWST(?) and NEO surveyor

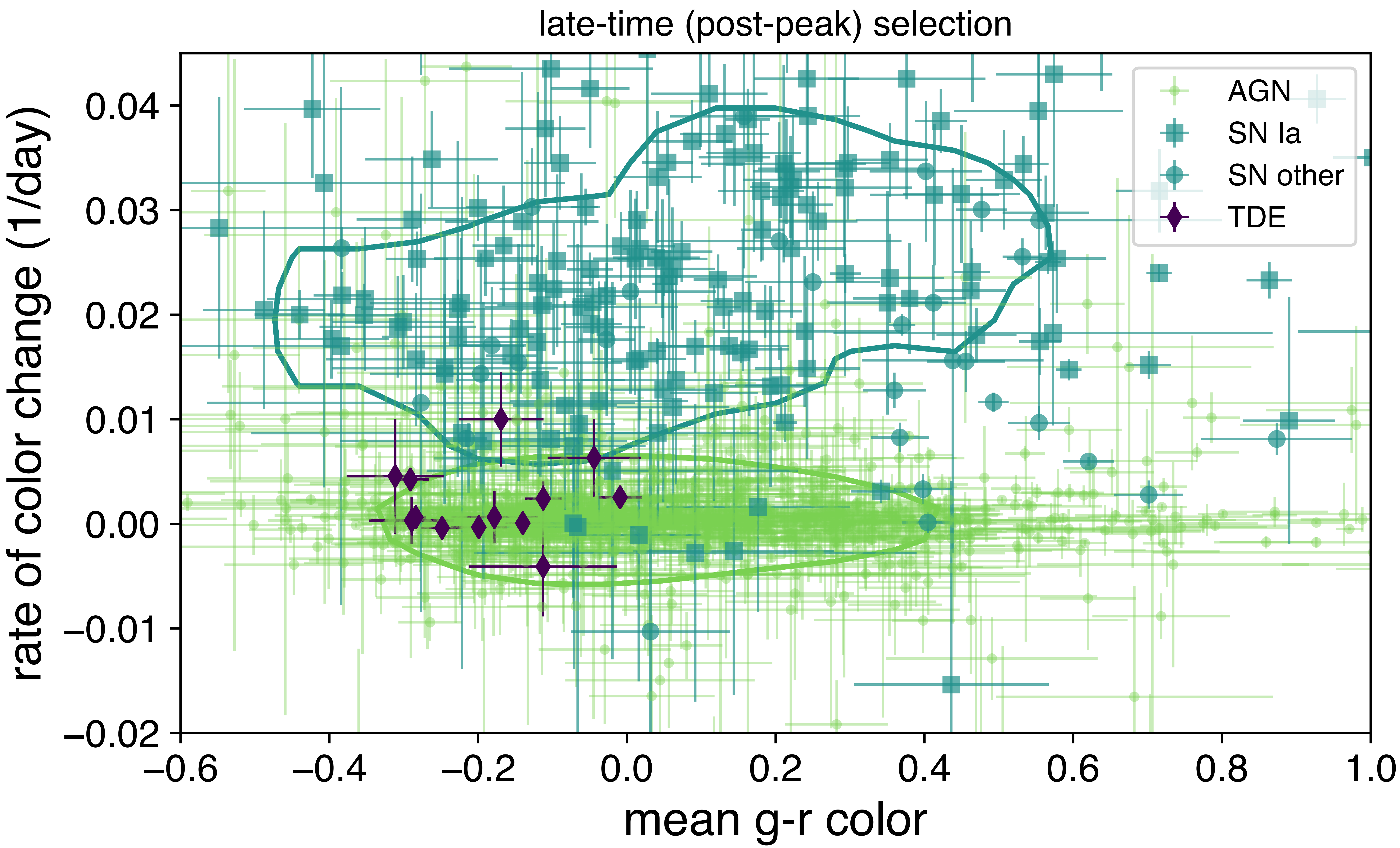
What is needed?

- **Data**: complement Rubin alerts for TDE *identification*
    - UV follow-up is key: ULTRASAT; UVEX; deep ground-based u-band
- **Data:** X-ray high cadence monitoring
    - Follow-up of optical- or X-ray selected sources
- **Theory**: explain extreme variability of AGN; connection to PeV particles

Thanks!

Backup slides

Photometric selection of TDEs with ZTF



A neutrino coincident with a tidal disruption event

Paintball-based significance (p=0.005)

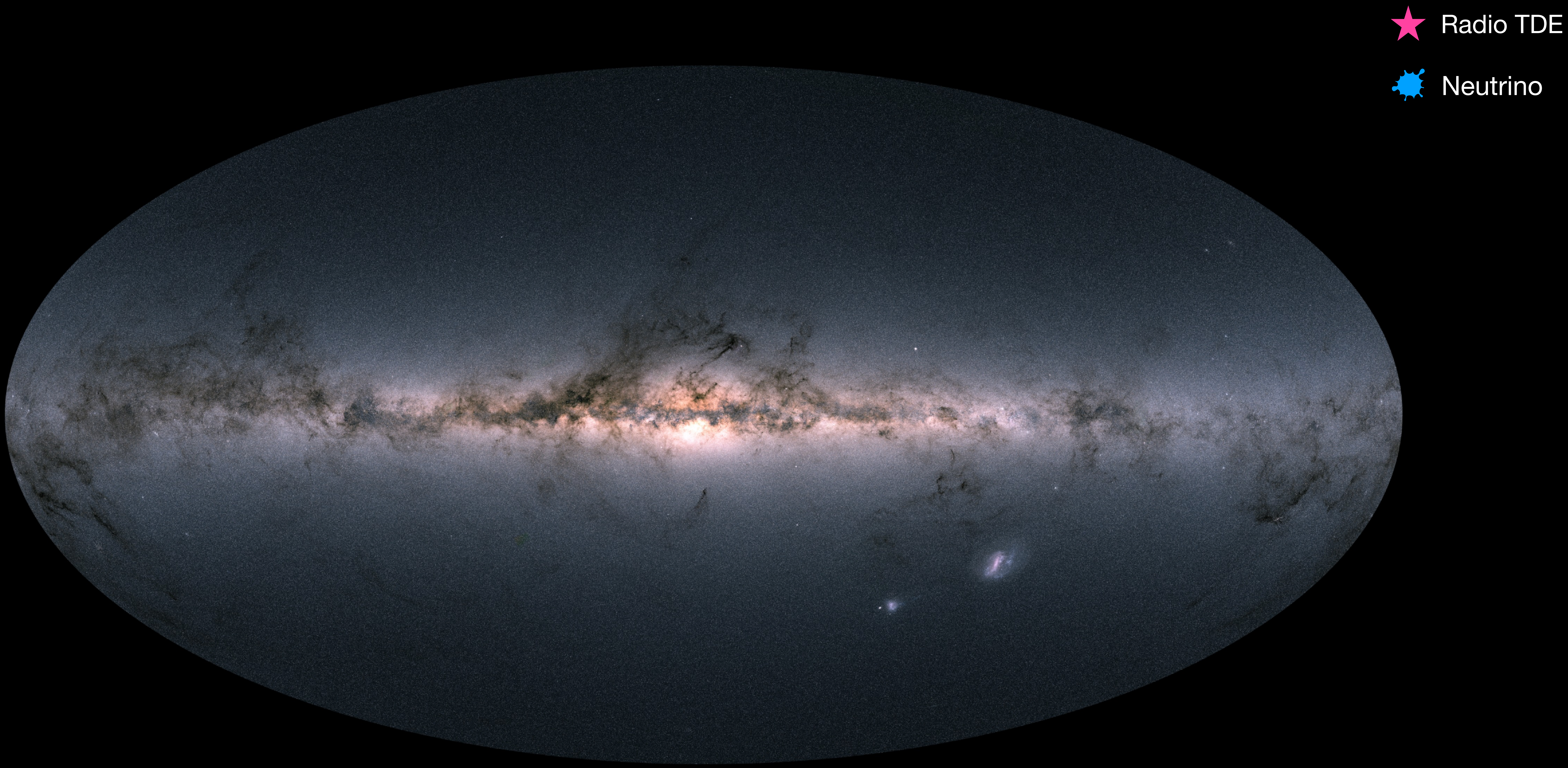


Image credit: Gaia/DPAC

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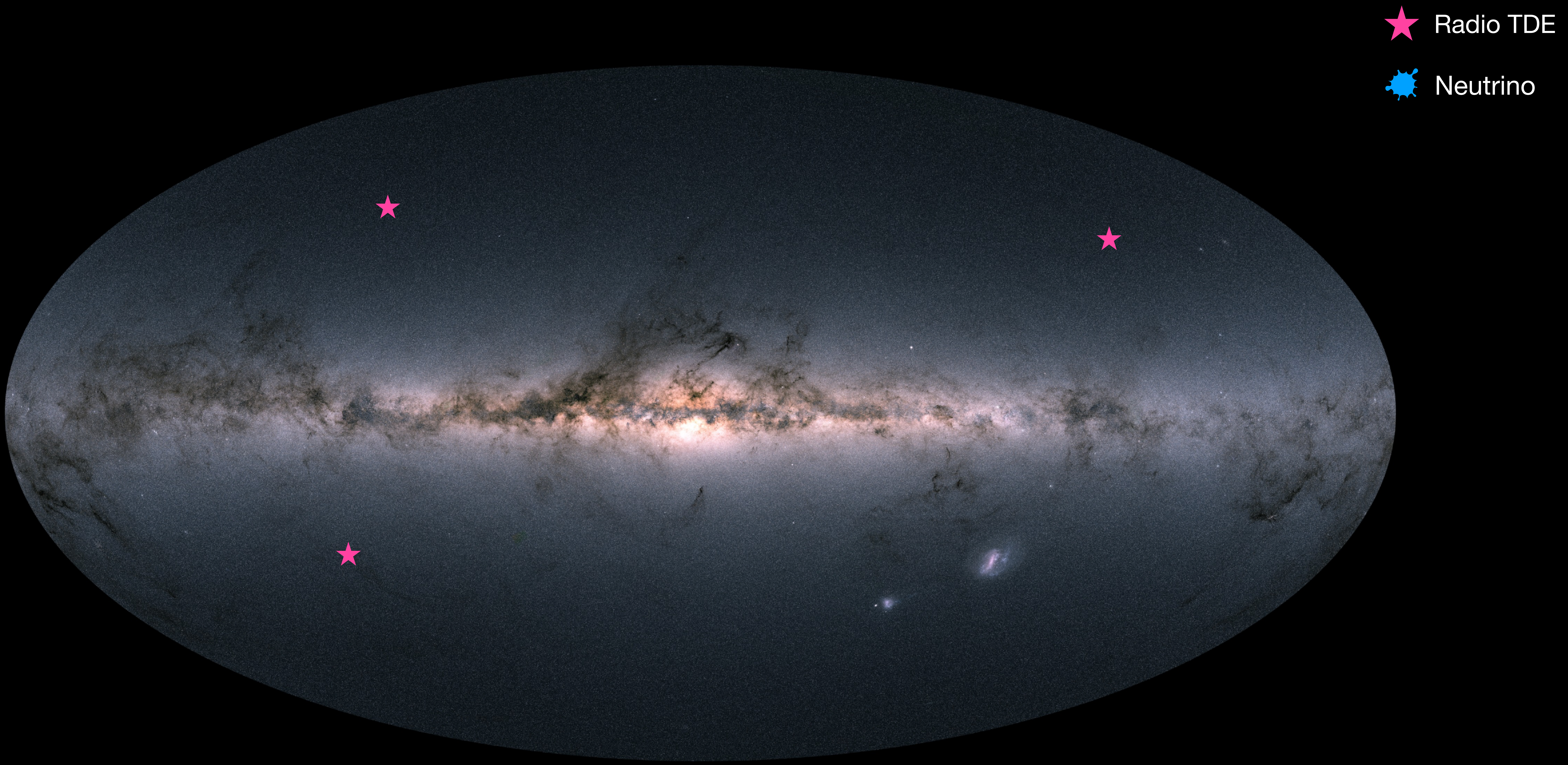

Image credit: Gaia/DPAC

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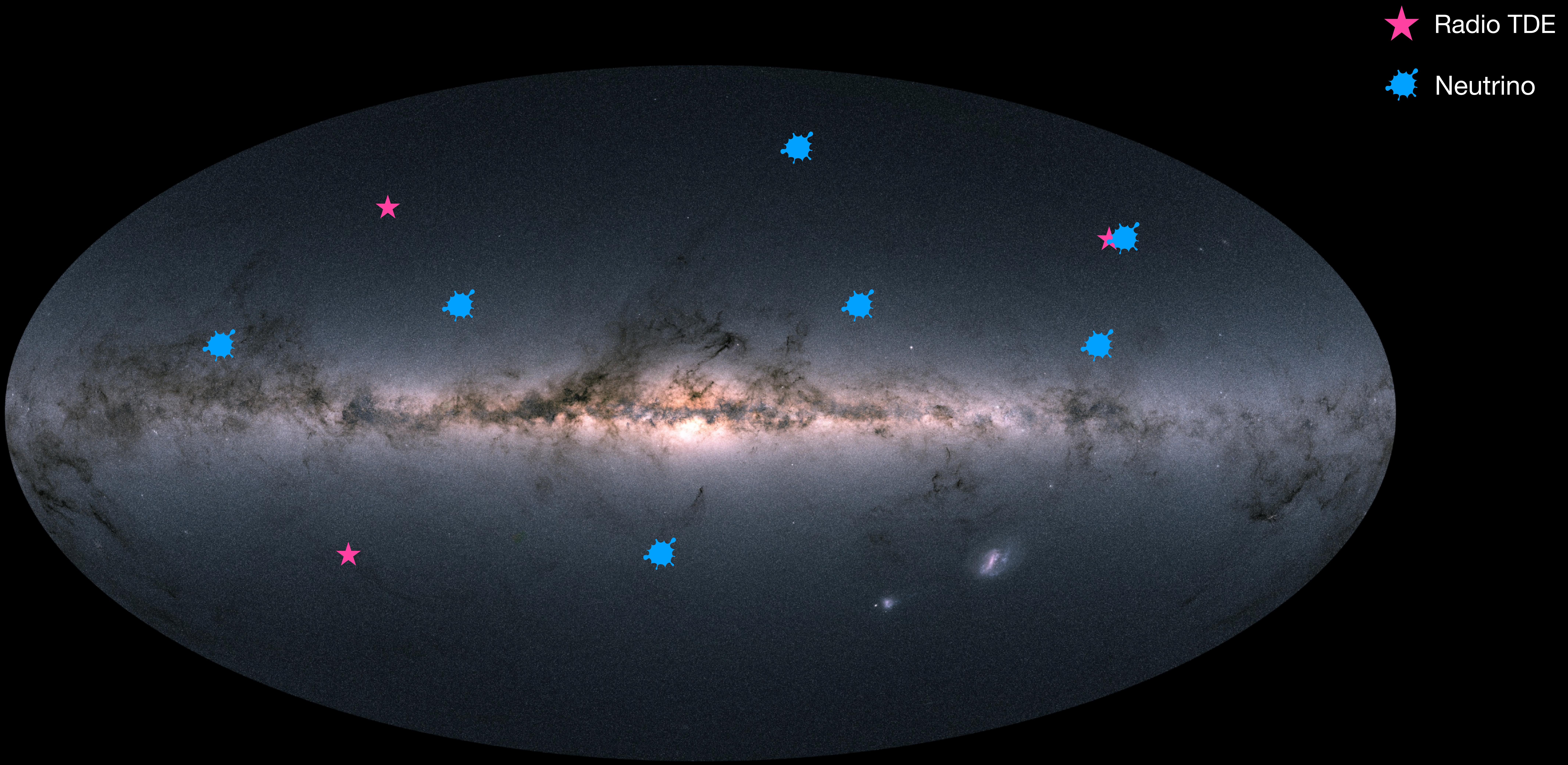
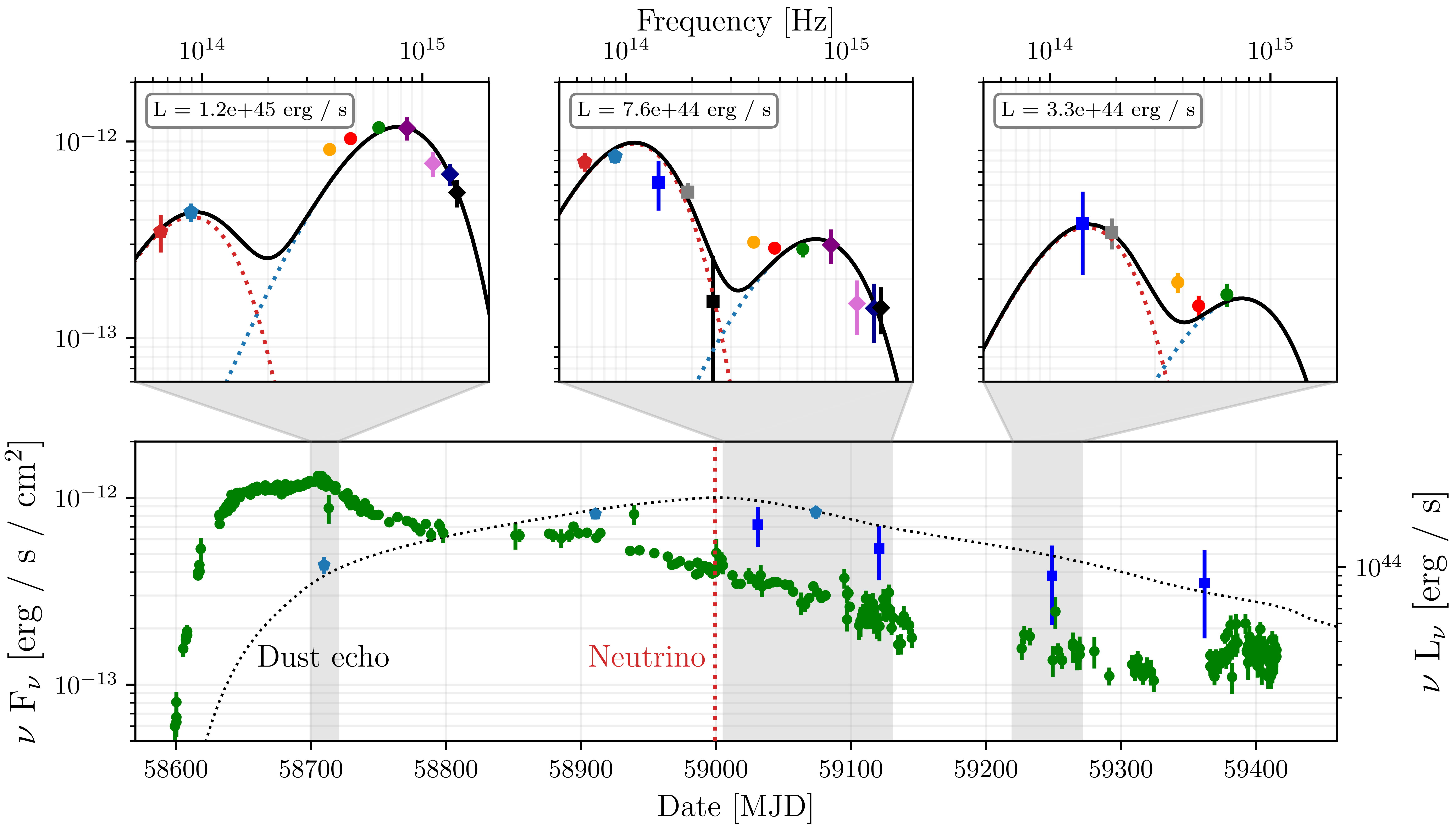
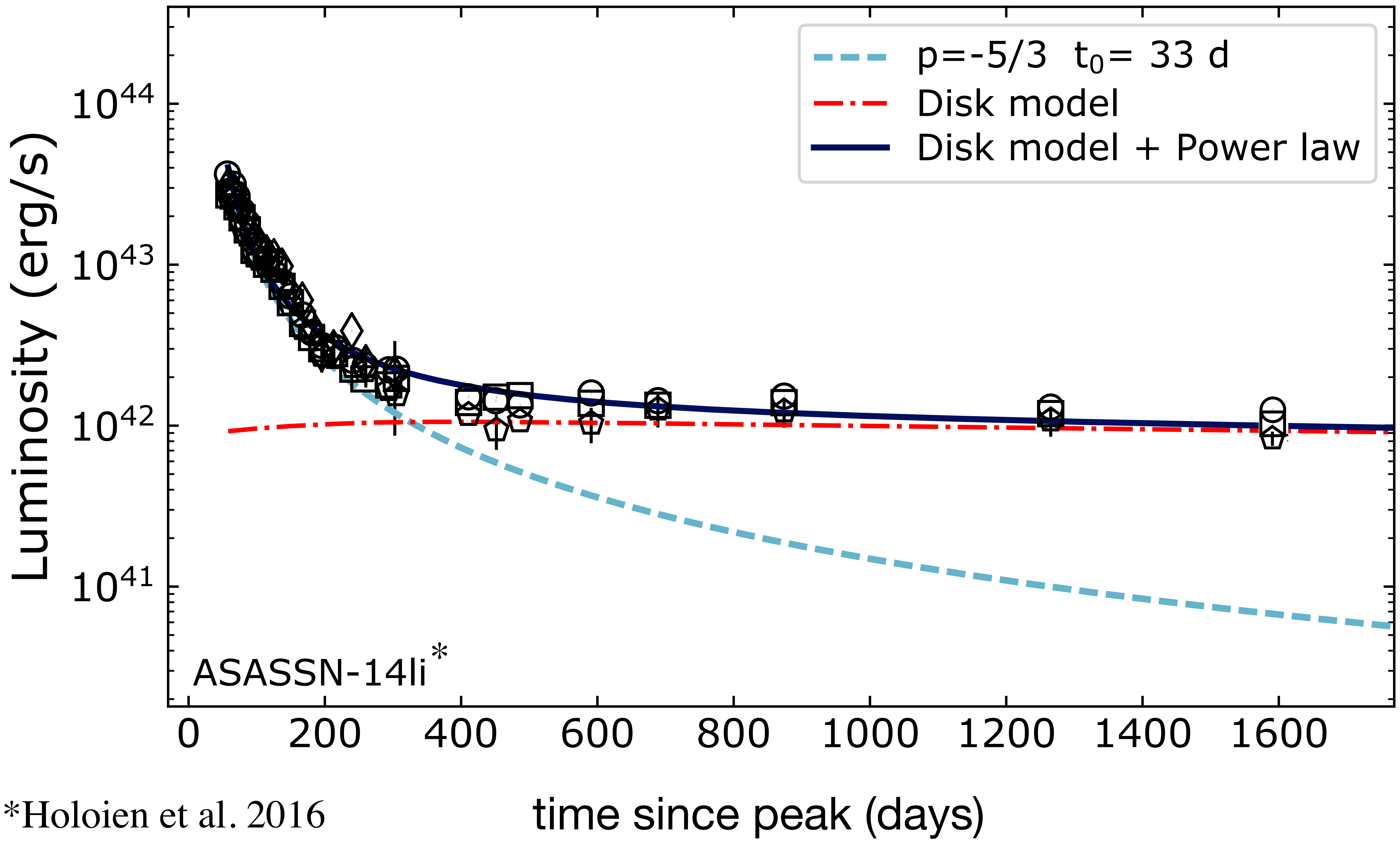


Image credit: Gaia/DPAC

AT2019fdr (TDE?): another large dust echo - Reusch et al (arXiv:2111.09390)



At late-times we see a disk

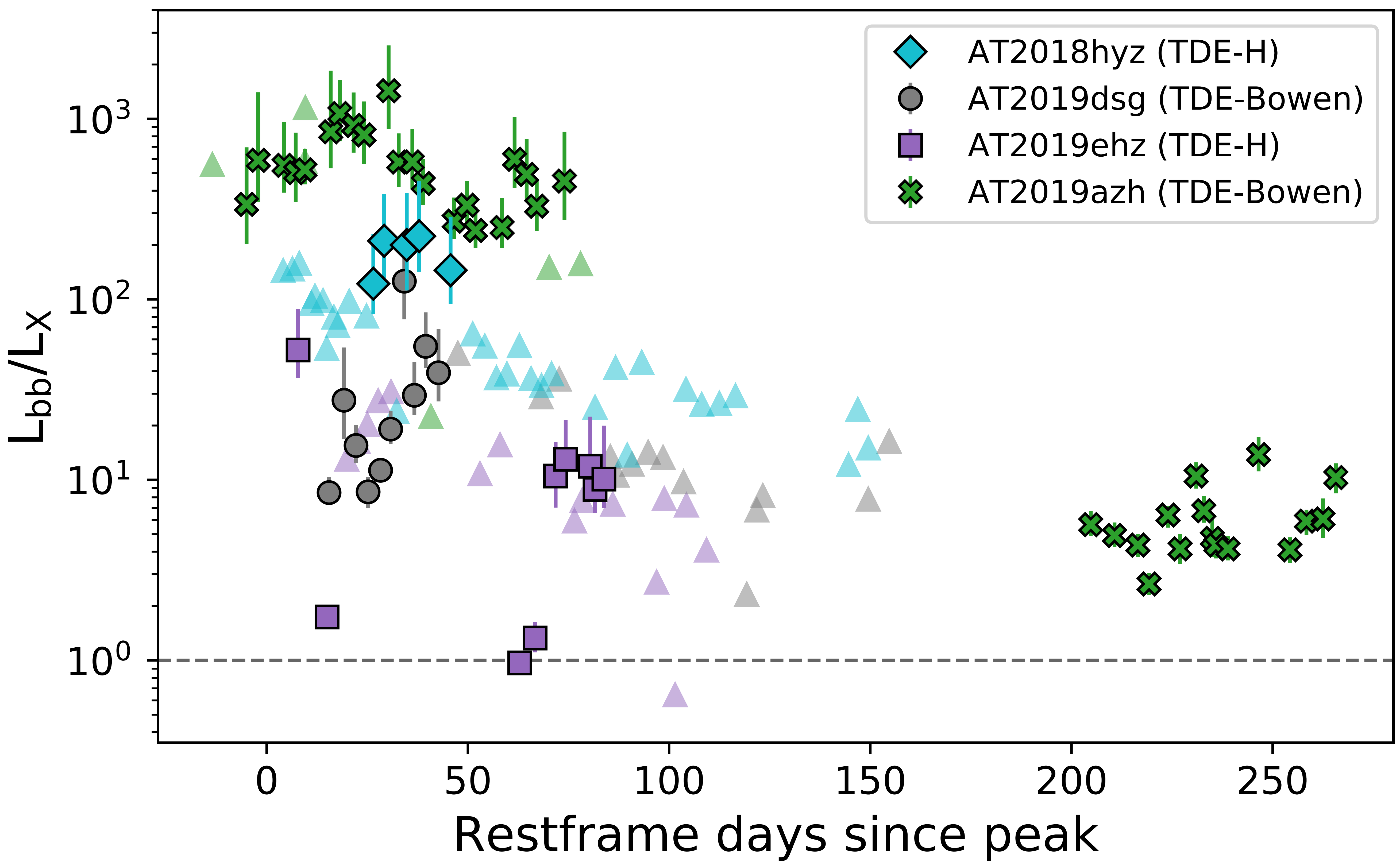


*Holoien et al. 2016

Common for late-time light curves
(van Velzen, Stone, et al. 2019)

Disk origin confirmed with late-time X-ray detections
(Jonker et al. 2019)

Surprising X-ray flares



- Flaring on ~day timescale
- Short "accretion events" of mass deflected from stream intersection point?
- Similar luminosity for optical/ UV and X-ray
- This ratio is naturally explained by small gaps in a reprocessing layer covering the X-ray emitting engine

URLs for movies:

https://www.desy.de/news/news_search/index_eng.html?openDirectAnchor=2030&two_columns=0

https://www.youtube.com/watch?v=-_dFQYQCmqk

https://www.nasa.gov/feature/goddard/2021/nasa-s-swift-helps-tie-neutrino-to-star-shredding-black-hole